2018

Sustainability of sprinkler- irrigated horticulture on sandy soils at Binningup - Swan Coastal Plain, W.A.

Eric Law
The University of Notre Dame Australia

Publication Details
Law, E. (2018). Sustainability of sprinkler- irrigated horticulture on sandy soils at Binningup - Swan Coastal Plain, W.A. (Master of Science (Thesis) (Arts & Sciences)). University of Notre Dame Australia. https://researchonline.nd.edu.au/theses/199

SUSTAINABILITY OF SPRINKLER-IRRIGATED HORTICULTURE ON SANDY SOILS AT BINNINGUP – SWAN COASTAL PLAIN, W.A.

Thesis submitted by

Eric Law

Masters by Research, Science

School of Arts and Sciences

University of Notre Dame Australia

Fremantle, Western Australia

May 2018

This page has intentionally been left blank.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The sustainability of sprinkler-irrigated vegetable crops in the Binningup–Myalup area of south-western Australia was investigated. The main crops are carrots, potatoes and onions. The crops are grown throughout the year in sandy soils and require large volumes of sprinkler irrigation during the summer growing period and little during winter. The irrigation water is extracted from the underlying superficial aquifer.

The combination of water with a relatively high salt content, evaporation between the sprinkler and the ground, and subsequent high evapotranspiration, leads to escalating soil water salinity during summer. At Binningup, the necessary horticultural practice of daily watering in summer to maintain soil moisture accumulates salts in the root zone of the crops at levels that inhibit yield and occasionally results in crop failure.

This investigation confirms the hypothesis that short-duration, high-volume winter rainfall events are sufficient to rinse accumulated salts from the soil profile each year and sustain current horticultural practice. Occasional high-volume rainfall in summer similarly rinses salt from the root zone. Thus, it is not the average volume of winter rainfall that ensures sustainability but the fortuitous occurrence of summer storms and high-volume rainfall in winter. It is shown that, even in a year of 50 per cent of average rainfall, the soil was rinsed and the aquifer replenished. It is also shown that after 10 years of production, the irrigation water supply monitored at the surface three to four metres, is stable in salinity and thus sustainable.

This research also investigated the effect of daily variation in both soil moisture and soil salinity on crop yield for vegetable crops, grown in identical soil structure during both the summer and winter periods. Alternative irrigation strategies were considered to evaluate whether sprinkler irrigation regimes can be modified to manage effective reduction of soil water salinity during the summer period to avoid loss of production or crop failure.

Data-logging equipment used to record soil moisture in the profile and water from rainfall and sprinkler irrigation provided indicative results. These records are supported by an adjacent online, real-time agricultural weather station and in situ tipping bucket rain gauges.

The results could modify reticulation regimes and enhance sustainability of both vegetable crops and the underlying aquifer resource.

DECLARATION OF ORIGINALITY

All the work and materials contained in this thesis are my own. To the best of my knowledge, any material that has been previously published or written by others has been duly referenced in the text. None of the work and material presented here has been previously submitted for the award of any other degree or diploma in any university or other institution.

Eric Law

ACKNOWLEDGEMENTS

I must firstly thank the research department at for their patience throughout the course of the thesis particularly during the final stages.

To my supervisor Dr Tim Meagher, thank you for your guidance and sharing with me, your broad and wide ranging ecological knowledge – it seems to know no bounds.

Dr Erik Paling, thank you for the assistance you provided ensuring standards and deadlines were met. Without that support (and a gentle shove), I'm not sure it would have made it.

James Dornan, early weekend mornings on the road to Binningup, supersized coffees at unsociable hours, road house breakfasts and long drives back to Perth after field trips. It was all worth it…maybe not the roadhouse breakfasts.

To the Dell'Agostino's who allowed us access to their operations and kept us informed with the all the practicalities of commercial horticulture … and endless supplies of carrots and potatoes.

The Fremantle Port Authority who provided the funding to enable the procurement of the monitoring equipment necessary for these investigations. Thank you for your support without which continuous monitoring would not have been possible.

My family, Mum and Dad who never thought it would happen after I jumped on a plane to work in all the remote corners of our land and oceans. To my friends, especially those in the corner who kept me sane and continuously reminded me about the big picture and the benefits of imbibing after long days and weeks in the library.

To my little bird Georgia Wren, hopefully you can look at this in years to come and know it's never too late to try something new.

ABBREVIATIONS

θ	soil moisture content
m_{dry}	dry soil weight
m_{wet}	wet soil weight
ASL	atmospheric surface layer
BOM	Bureau of Meteorology (Australia)
BREB	Bowen ratio-energy balance
dS/m	decisiemens per metre
DAFWA	Department of Agriculture and Food Western Australia
EC1:5	electrical conductivity of a soil suspension at a ratio of 1:5
EC	electrical conductivity
ECse	electric conductivity of a saturated paste
ECsw	electrical conductivity of soil water
E_p	pan evaporation
ET	evapotranspiration
ET_0	reference evapotranspiration
IBRA	Interim Biogeographic Regionalisation for Australia
kPa	kilopascal
PIRSA	Primary Industries and Regions South Australia
ppm	parts per million
S/m	siemens per metre
TDR	time–domain reflectometry

TDS	total dissolved solids
θg	gravimetric soil water content

CHAPTER 1. INTRODUCTION

1.1 Overview

Vegetable production by sprinkler irrigation on the Swan Coastal Plain of south western Australia extends from Gingin in the North, to Binningup and Myalup in the south (Figure 1-1). The soils on the Swan Coastal Plain are aeolian and contain less than 3% clay and 1% organic carbon (Prince et al. 2008). Commercial production areas do have an underlying superficial aquifer at shallow depth, with a surplus supply of water for sprinkler irrigation (Mackay 2014) but it is anecdotally accepted that summer crops occasionally fail or experience a reduction in yield, despite this water availability. To date there has been no definitive publication on the sustainability of the industry, particularly in regard to the widely anticipated reduction in rainfall due to climate change.

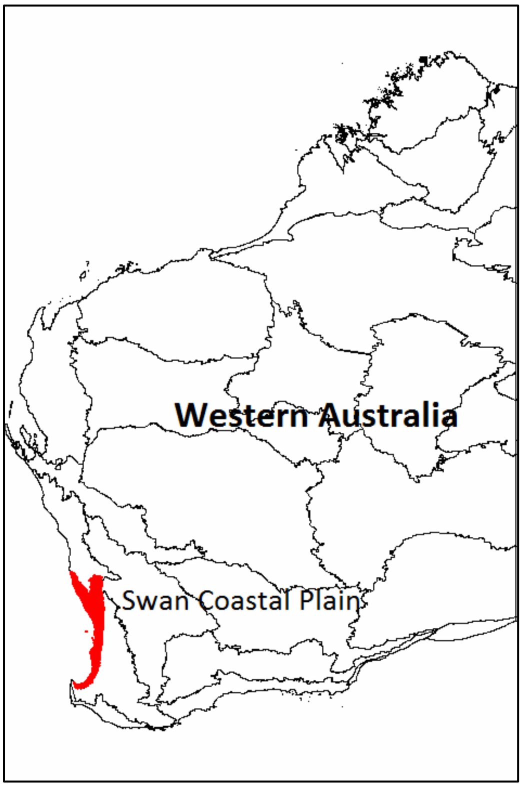

Figure 1-1: Swan Coastal Plain, Western Australia (Source: DoE 2015).

This investigation was prompted by the findings of research by Dr Tim Meagher (Unpub. Obs.) that was conducted in support of a licence for sprinkler irrigation at a vegetable farm at Binningup (Figure 1-2). The findings, which were essential to the aims of the current investigation, were summarised by Meagher (2010).

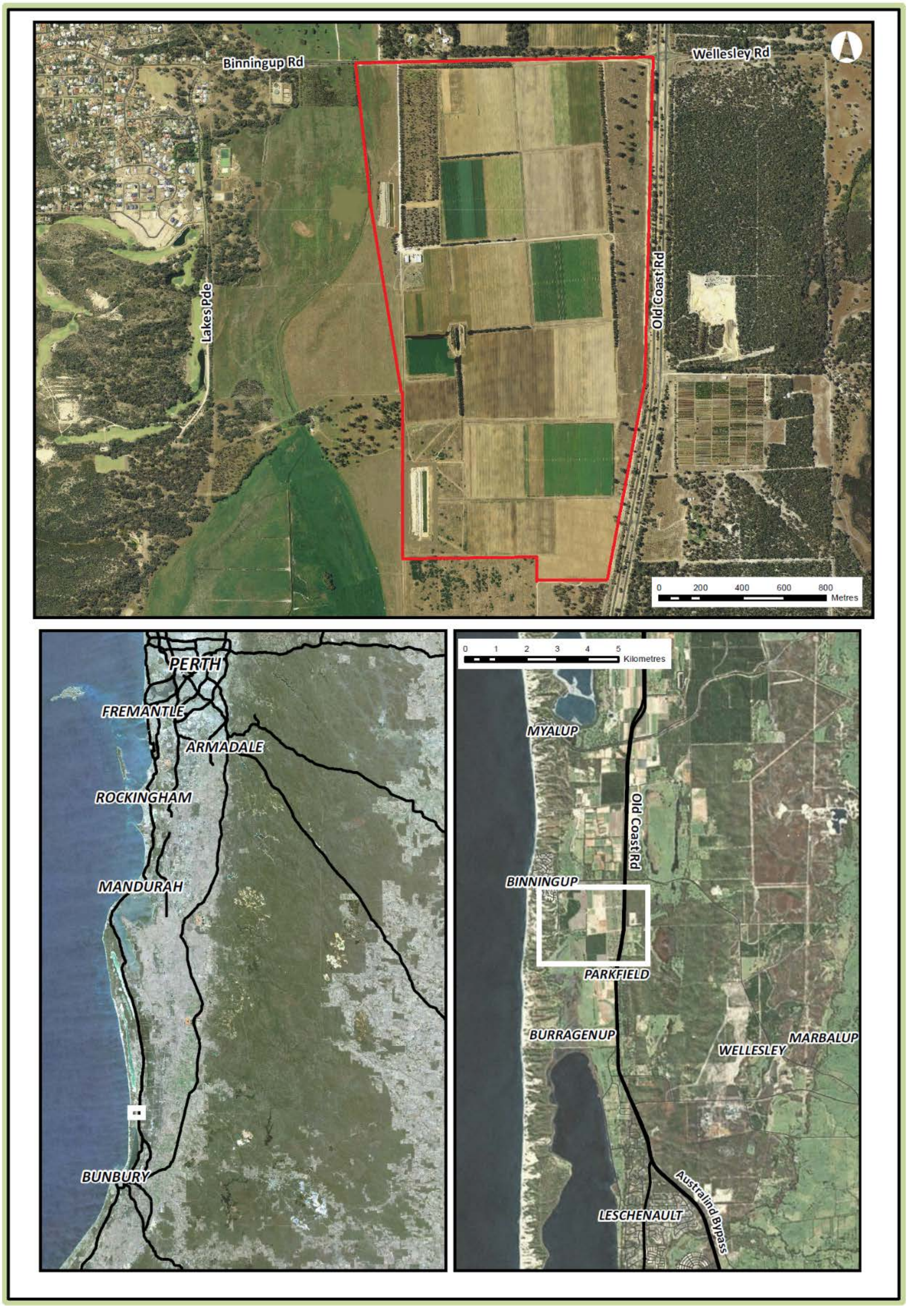

Figure 1-2: Research project location – Binningup, Western Australia.

At Binningup, while crops of mainly carrots, potatoes and onions are grown throughout the year, during summer they require a large amount of water. This is due to a combination of high soil porosity, low relative humidity, substantial wind and high temperatures. As a result of the seasonal climatic conditions, very little sprinkler irrigation is required during winter.

Studies by Libutti and Monteleone (2012) and Monteleone and Libutti (2012) noted that, where irrigated agriculture is practiced in Mediterranean climates such as the study location, rainfall during the winter period played an important role in removing salts accumulated in the soil by summer irrigation. In addition when annual rainfall is too low to prevent salt accumulation, the practice of leaching through irrigation is recommended, given that the soil has sufficient permeability and the water table is at a depth that prevents any capillary rise to the root zone (Monteleone et al. 2004).

Licence holders in Western Australia are required to log the volume of water they draw from the aquifer and thus pumps at the research site were fitted with accurate meters. Meagher (2010) analysed the water production onsite and described a substantial seasonal variation in water requirement (Figure 1-3 and Figure 1-4).

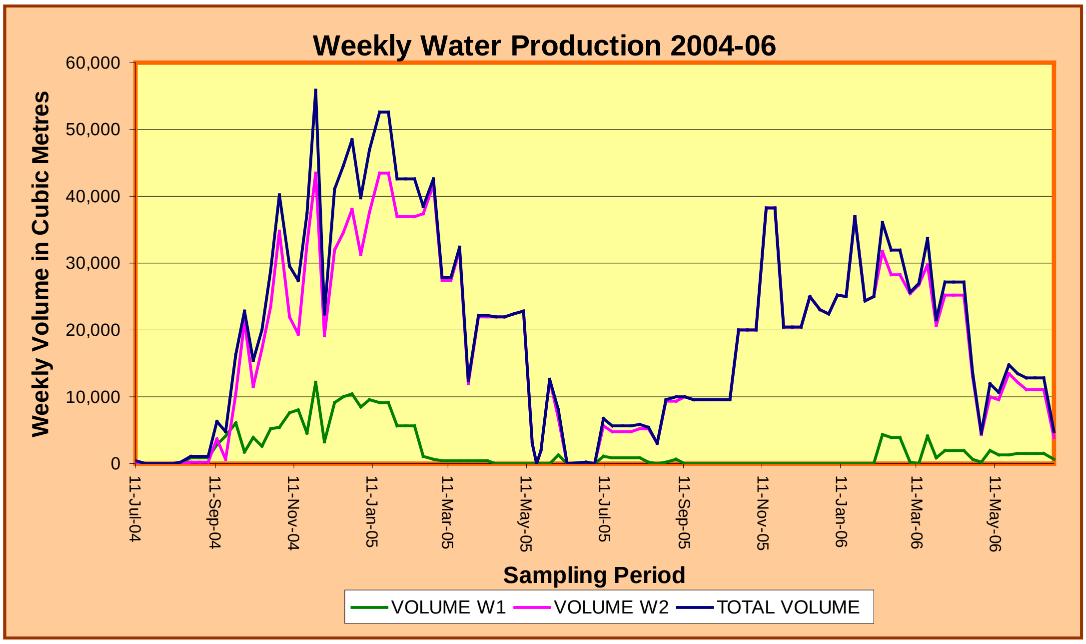

Figure 1-3: Water production from 2004–2006 (Meagher 2010).

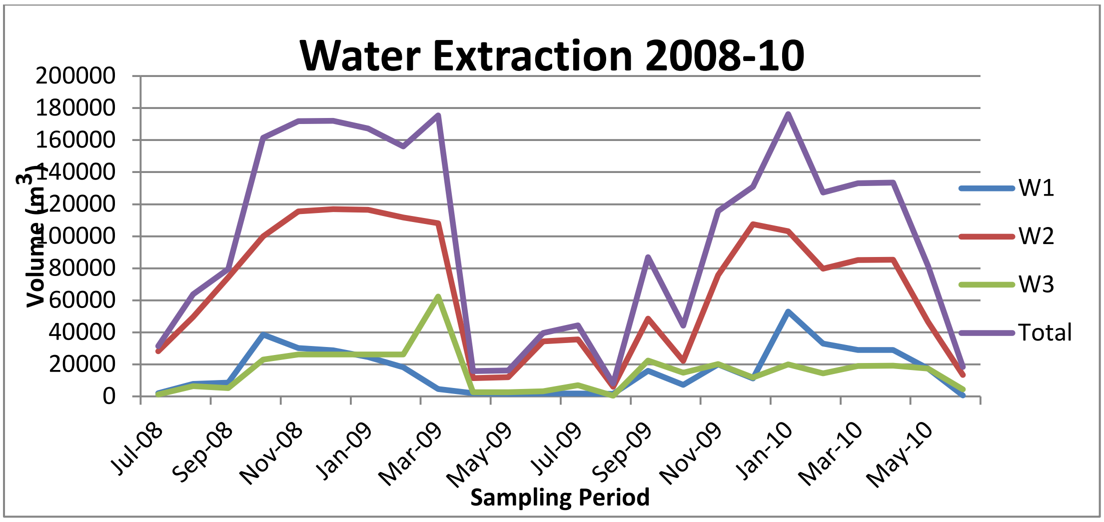

Figure 1-4: Water production 2008–2010 (Meagher 2010).

Meagher (2010) also noted that water quality began at 600–800 ppm of total dissolved salt (TDS) but after a few years of production, it increased and stabilised at 900–1,300 ppm TDS. Commander (1988) described the superficial aquifer beneath the Binningup study site as occurring in ~18 m thick karst and increasing in TDS with depth. An additional piece of information for this study's inception was a report by Rockwater (2000), which concluded, based on monitoring bore piezometric data, that groundwater would take approximately eight years to flow from the east side of the research project location to the excavations into the aquifer that supplied the irrigation water. This led to the question of whether evapotranspiration of sprinkler irrigation was responsible for the observed increase in TDS and that would eventually make crop production unsustainable.

The component of the unconfined aquifer underlying the study site occurs in a formation that is commonly referred to as the 'Tamala Limestone' which continues to both the north and south of the research area. However, there is a sharp demarcation immediately to the east where the superficial aquifer continues in a silica sand formation known as the 'Bassendean Sand'. The stratigraphy is described by Commander (1988) and in more detail by Semeniuk (1995).

A vegetable farm site at the research location shown on Figure 1-2 was closely monitored for water use in relation to the production of carrots, potatoes and onions between March 2011 and January 2012. The same crops are grown year-round. However there is a difference in both growing periods and associated sprinkler requirements. The summer period is in the order of 17 weeks compared with 24 weeks for the winter period with a comparable yield.

Daily variation in soil moisture and soil water salinity during the crop cycle was investigated in relation to varying evaporative conditions and parameters included; temperature, wind speed, humidity and solar radiation. Accurate records of the area of crop, fertiliser application and volume of water used for each crop are maintained by vegetable producers. Salinity in the upper aquifer layers is known to increase through evapotranspiration via irrigation water and its return of salts. It is also understood that high-volume pumping via bores may draw more saline water from deeper in the aquifer and it is for this reason that local vegetable farmers install ponds and do not use bores. Therefore, appropriate irrigation practices are required to prevent continued increases in soil salt concentrations.

The soil water balance throughout a crop is known to limit crop quality and production (PIRSA 2006). If too much water is applied, fertiliser nutrients are rinsed past the root zone and into the underlying aquifer. If too little water is applied, there is the possibility of salt accumulation due to water losses through the sprinklers and evapotranspiration by the crop. Thus it is common horticultural practice to balance the volume of irrigated water applied to the crops so as to saturate the soil no deeper than the crop root zone for plant uptake (Fares and Alva 2000; Money 2000). An investigation by Schoups et al. (2005) on irrigated agriculture in the San Joaquin Valley, California also noted that for irrigated agriculture to remain sustainable, a soil/salt balance must be maintained that allows for a productive cropping system avoiding salt build-up in the soils and groundwater which threatens both productivity and sustainability.

It has also been recommended in Monteleone et al. (2004) that periodic leaching should be applied when soil salinity reaches the threshold concentration where crop yield is adversely affected. The physical characteristics of the sandy soils overlying the property enable 100% infiltration of rainfall and/or applied water which optimises leaching potential.

Before horticulture at the property, a Tasmanian blue gum (*Eucalyptus globulus*) plantation was trialled and in order for this to occur, the land was cleared of Tuart trees (*Eucalyptus gomphocephala*), a species currently in decline on the Swan

Coastal Plain. Evidence of the Tuart woodland exists in the Coastal or Tamala Limestone as solution channels.

1.2 Research objectives

The three main objectives of this research were:

- To record the behaviour of both rain and sprinkler water in the crop soil profile in response to the age of the crop and ambient meteorological conditions.
- To record salt accumulation from sprinkler water in the soil profile and determine the intensity and duration of rainfall required for effective leaching of the soil profile.
- To determine the replenishment of the aquifer below the crops and whether there was a significant accumulation of salt in the upper portions of the aquifer.

1.3 Research purpose

The purpose of this research was thus to find out if seasonal rainfall in Binningup was sufficient to effectively rinse the soil profile of salts and replenish the irrigation source water to sustain horticultural activities. In addition, it was hoped that this research would allow horticultural managers to develop an optimal regime of summer irrigation for salt reduction, fertiliser efficiency and crop yield.

At a local level, this research has been essential in determining the sustainability of irrigated vegetable production in the Myalup–Binningup area. Crops have failed in recent summers due to increased salinity of reticulation water and some water supplies are now too saline for reticulated irrigation (M. and P.G. Dell'Agostino, pers. comm.).

This research thus not only has potential significance in relation to the local (WA) domestic economy (supply, demand and water use) - there is the potential for domestic and commercial watering regimes across the Swan Coastal Plain to benefit in the long term as a result of the findings - but could also be used as a model with wide-reaching applications to irrigated horticultural practices that occur on sandy soils globally.

The overarching objective of the research was to provide an assessment of the sustainability of irrigated horticultural practices on a property with the given physical characteristics and associated environmental conditions on a local scale – and if possible extrapolate to a global scale where properties face similar challenges. This required investigations on vegetable growth; soil moisture; soil and soil water salinity; and groundwater quality and movement beneath the property. As this was the focus of the investigation, soil physical and chemical properties were investigated during the research only inasmuch they influenced soil/salt water balances.

1.4 Thesis structure

The thesis begins with a detailed review of literature relating to the different aspects of the research project, with local national and international context. The physical characteristics of the research site are described in Chapter 3, including the geology and overlying soils in which the crops are grown; the underlying groundwater from which the irrigation water is sourced and the meteorological conditions affecting them.

Methods and materials used during the key investigations are described in Chapter 4 which leads into the investigation results for rainfall and irrigation application; soil water content; and crop salinity of both winter and summer crops.

The discussion draws on similar research and other literature previously described within the body of the thesis and is followed by the conclusions made from the investigation outcomes individually and holistically, against the research objectives.

CHAPTER 2. LITERATURE REVIEW

The primary focus of this investigation was to determine if seasonal rainfall in Binningup was sufficient to effectively rinse the soil profile of salts and replenish the irrigation source water to sustain horticultural activities. In order to place the data collected in perspective, it is thus necessary to review the literature related to various facets of the research. This review begins with a discussion on irrigated horticulture in Western Australia, its sustainability and the general effects of irrigation upon soil. Next is a discussion on plant water demand, its measurement and the concept of soil water balance. This is followed by a description of soil water dynamics and the current methods of measuring soil water content. The review concludes with a review of soil water salinity, plant tolerance thresholds and leaching.

2.1 Irrigated horticulture in Western Australia

Irrigated horticulture is conducted widely across Western Australia and particularly within the Perth metropolitan, South West, Kimberley and Gascoyne districts. The main growing areas are in the South-West, on the Swan Coastal Plain from Gingin to Busselton, and inland around Manjimup and Albany (Mackay 2014; DAFWA 2015a). In 2013, vegetable production in Western Australia had a farm gate value of approximately \$336M within a total industry valued at \$909M (DAFWA 2015b). Most vegetables are grown for local consumption but carrots are also exported year round to markets in South East Asia and the Middle East (Phillips 2005).

The sandy soils of the Swan Coastal Plain contain less than 3% clay and 1% organic carbon and are augmented by ploughing in cover crops and vegetable crop remains to increase the humic content. The improved soils are still coarse textured however and have a low moisture holding capacity requiring daily irrigation during the summer growing period (Lantzke 1995; Phillips 2005). This can also result in a high percentage of applied fertiliser being leached below the root zone into groundwater (Prince et al. 2008)

Achieving the correct balance between available crop water, fertiliser use, crop yield and leaching is essential to the sustainability of vegetable production on the sandy soils of the Swan Coastal Plain (O’Malley and Prince 2010). It should be noted however that the coarse nature, low clay content, high hydraulic conductivity and low field capacity of the soils require that near field capacity is maintained in order to achieve optimum yields (Prince et al. 2008). The Mediterranean climate and maritime influence in coastal areas of south-western Australia make growing particular crops, such as potatoes and carrots, possible for 12 months of the year.

Currently well-managed, good quality groundwater supply is available for irrigation purposes (Phillips 2005; Mackay 2014) and unconfined aquifers underlying horticultural properties on the Swan Coastal Plain are the major source of water. Because of this, efficient water use and minimal loss is integral to maintaining vegetable production (O'Malley and Prince 2010).

Source water is available for crop application by sprinkler irrigation during the day or night and in the Binningup–Myalup area, overhead sprinkler irrigation is predominantly used for vegetable production. However, irrigation at night is not considered suitable for sandy soils, as plants do not use the water and it drains rapidly after irrigation (Lantzke 1995; Bavi et al. 2009).

2.1.1 Sustainability of irrigated horticulture

Irrigation is necessary for horticultural production on the Swan Coastal Plain but concerns have arisen about sustainability due to decreasing rainfall patterns, exploitation of water resources and land use competition (Dodd et al. 2010). The primary objective of irrigation is to provide a crop with sufficient and timely amounts of water in order to avoid yield loss (Ayers and Westcot 1985). However, if evaporation is high, losses of up to 45% can occur (Uddin et al. 2014) and, coupled with groundwater salinity above 600 ppm, salts in the applied water may accumulate in the soil.

Fares and Alva (2000) describe industry and best management practices in irrigation which were designed to minimise leaching of water and nutrients below the root zone while maintaining adequate irrigation water within the crops roots. By accurately applying water to meet crop requirements irrigators can achieve high water use efficiency resulting in a reduction in the amount of water flushing through the root zone (Fares and Alva 2000; Money 2000).

However Biswas et al. (2009) reported that salt levels were rising in horticultural crops in many major irrigation districts, even with efficient management and winter leaching following rainfall. Thus increased irrigation efficiency is being sought to conserve water, reduce drainage and to mitigate some of the water pollution associated with irrigated horticulture (Rhoades et al. 1999) and in order to sustain economic viability, irrigators must increase production efficiency (Flowers 2004). However, each location has its limitations; for example, at Binningup, there is surplus water, very high evapotranspiration and marginal, if not limiting, salt levels.

2.2 Effects of irrigation on soil

Infiltration can be affected not just by water quality but physical and chemical characteristics of the soil including exchangeable cations (Ayers and Westcott 1985). Irrigation results in large increases in the amount of water passing through the soil profile which has the potential to accelerate weathering, leach material and change soil structure. Poor quality water can therefore cause critical damage to soil structure (Murray and Grant 2007).

Mechanical stresses can also damage soil structure and these include the impact of water droplets from rain or irrigation, which disrupts soil already weakened by its water content (Lehrsch and Kincaid 2006; Murray and Grant 2007). This results in physical disintegration known as slaking, as well as soil compaction caused by the impact of rain or irrigation water itself (Batey 2009; Shainberg and Letey 1984).

The two main processes determining water movement through a soil are it’s infiltration rate and hydraulic conductivity (Shainberg and Letey 1984). If these processes are adversely affected by irrigation water quality there is also the potential to reduce the effectiveness of leaching.

2.2.1 Irrigation water quality

In terms of salinity, a number of factors determine the suitability for irrigation water including the type and amount of salts present, the soil type, plant species and growth stage (Warrence et al. 2002).

Two primary water quality factors that determine how irrigation water will affect soil structure and stability are salinity or electrical conductivity (EC) of the water and sodium adsorption ratio (SAR) given by: SAR = $[Na^+] / \sqrt{([Ca^{2+}] + [Mg^{2+}])}$ where $[Na^+]$, $[Ca^{2+}]$ and $[Mg^{2+}]$ refer, respectively, to the concentrations (in milli-moles/L) of sodium, calcium and magnesium in solution (Ezlit et al. 2010).

Calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) generally comprise almost all of the exchangeable cations in soil. In relation to soil structural stability, SAR is an expression of the balance between the concentration of an undesirable cation sodium (Na) and those of more desirable ones (Ca, Mg; Murray and Grant 2007).

Salinity has a direct physical effect on soil structure generally as a result of high concentrations of sodium, so that the cation exchange capacity of soil irrigated with saline water becomes populated with sodium (Murray and Grant 2007). Tedeschi and Dell'Aquila (2004) noted that irrigation with saline water led to an increase in the percentage of exchangeable sodium and degradation of the soil's physical properties.

2.3 Plant water demand

Determining plant water demand requires the measurement of evapotranspiration (ET), a term used to describe the water loss occurring from the processes of evaporation and transpiration (Critchley et al. 1991). Factors affecting evapotranspiration include solar radiation, air temperature, humidity and wind speed; crop characteristics including crop type, variety and development stage; and management and environmental aspects (Allen et al. 1998).

Evapotranspiration can be measured either directly or determined indirectly from weather data and soil water balance (Zeleke and Wade 2012). Direct measurement requires specific devices and accurate measurements of physical parameters or the soil water balance (Allen et al. 1998). Measurement systems include: lysimeters, eddy covariance, Bowen ratio, water balance, as well sap flow, scintillometry and satellite-based remote sensing and direct modelling (Rana and Katerji 2000; Allen et al. 2011). These methods can be expensive, demanding in terms of accuracy of measurement and require competent personnel (Allen et al. 1998; Sumner and Jacobs 2005). A few are examined below.

2.3.1 Lysimeters

Weighing lysimeters were developed to give a direct measurement of evapotranspiration and consist of a container filled with soil, resting on a scale. The container prevents loss of water to deep percolation or lateral water movement, allowing water losses only through the soil or through the crop planted in the lysimeter (Evett et al. 2009). By isolating the crop root zone from its environment and controlling the processes that are difficult to measure, different parameters in the soil water balance equation can be determined with greater accuracy (Allen et al. 1998).

2.3.2 Energy balance and microclimatological methods

In these methods, only the transfer of heat as sensible heat flux is considered and evapotranspiration (latent heat flux) is calculated as the residual term in the general energy balance equation (Ershadi et al. 2011). Common approaches include the Bowen ratio-energy balance (BREB) which can be obtained independently of weather conditions and requires no information about aerodynamic characteristics (Shi et al. 2008); and eddy covariance, which measures vertical turbulent fluxes in the atmospheric surface layer (ASL) by sensing the properties of eddies as they pass through a measurement level (Allen et al. 1998).

2.3.3 Soil water balance

The soil water balance method assesses the incoming and outgoing water flux into the crop root zone over some time period. Irrigation and rainfall add water to the root zone and part may be lost by surface runoff or deep percolation which eventually recharges the water table. Water may also be transported upward by capillary rise from a shallow water table towards the root zone (Allen et al. 1998).

The time and cost associated with direct measurements of evapotranspiration make the use of methods relying on more easily obtainable data more desirable. One such method is the Penman–Monteith equation (PM), which requires measurement of net radiation, soil heat flux, air temperature, relative humidity, wind speed, and other environment-specific variables. Another is pan evaporation (E_p) which requires measurement of daily evaporation from a pan. A third is reference evapotranspiration (ET_0) which can be derived from PM and E_p and requires measurement of incoming solar radiation, air temperature, relative humidity, and wind speed (Sumner and Jacobs 2005).

Empirical equations developed for assessing crop or reference crop evapotranspiration from meteorological data include the Penman-Monteith method which is considered a standard method for evapotranspiration estimation in agriculture (Allen et al. 1998; Zeleke and Wade 2012) and is often used to verify other empirical methods (Chen et al. 2005).

Evapotranspiration estimated from pan evaporation measures the evaporation from an open water surface providing an index of the combined effect of radiation, air temperature, air humidity and wind on evapotranspiration, however differences in the water and cropped surface may produce significant differences in the water loss estimate from an open water surface compared to that of the crop (Allen et al. 1998).

2.4 Soil water dynamics

Maintaining sufficient soil water content and quality is required to support optimum plant growth and product yield (Fares and Alva 2000). The state of water in soil is described in terms of the amount of water and the energy associated with the forces that hold the water in it (Bilskie 2001). Where soil water content is an indication of the amount of water present, soil matric potential determines the availability of water to plant metabolism and is a direct indication of the energy required for plants to obtain water from the soil (Irmak et al. 2006).

Soil water content is expressed as the mass of water in a unit mass of soil (gravimetric) or volume of water in a unit volume of soil (volumetric) (Gardener et al. 2000; Bilskie 2001; Charlesworth 2005). When soils dry, more energy is required to extract available soil water (Charlesworth 2005) and this is measured in kilopascals (kPa, Mullins 2000).

Irmak et al. (2006), describe total soil water potential as 'the sum of gravitational, osmotic and matric potential where gravitational and osmotic potential are generally not taken into account'. Hydraulic conductivity refers to the ease of water movement through soil, both horizontally and vertically, and it decreases with a decrease in pore size and water content (McCauley 2005). Therefore, the hydraulic conductivity of a soil will vary and be at its greatest when soil is fully saturated (Warrence et al. 2002).

The rate of soil water movement (e.g. Figure 2-1) is therefore determined by its ability to conduct water, evaporative demand, the temperature, and the pressure and salt gradients which change over the course of a day (Jackson 1973).

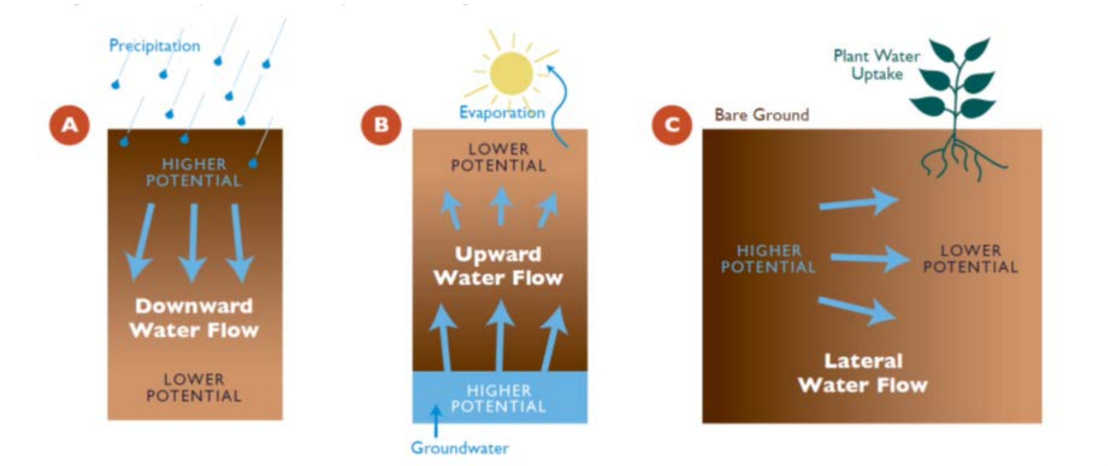

Figure 2-1: Three basic pathways of water movement through the soil profile (Source: McCauley 2005).

King and Stark (2005) describe the influence of a soil's water holding capacity on irrigation system design and irrigation scheduling and note that water should be able to be repeatedly applied before crop water stress develops.

2.4.1 Diurnal variation in soil moisture

While water for transpiration is abstracted from the soil, precipitation, irrigation and groundwater variously add water to it. Also, whereas precipitation and irrigation could directly evaporate without adding to soil water, soil water adds to groundwater (via gravimetric drainage) as well as takes from it (via capillary rise) (Moiwo and Tao 2015).

In a soil without vegetation and active rainfall, the soil moisture at the surface has a marked daily variation as it dries during the day and partially rewets at night. The near surface inter-particle space dries and draws moisture from below to be lost in the following cycle, until a stable gradient is established. The daily variation in soil moisture decreases with both depth and decreasing soil temperature (Villagarcía et al. 2004) and plays a significant role in the evaporation of water from soil. Thus atmospheric variables, such as radiation, wind, air temperature and humidity all influence the physical condition of the soil surface and determine the course of evaporation (Jackson 1973).

Importantly, salt concentration in the crop root zone continually changes with moisture change. As the soil dries, the soil solution becomes increasingly concentrated, reducing the plants access to soil water (Allen et al. 1998; Sheldon and Menzies 2004).

Soil moisture in the unsaturated zone near the soil surface also plays a critical role in partitioning rainfall into surface runoff, evaporation and groundwater recharge (Yijian et al. 2009). Evaporation rates will vary with the season soil water content, and movement within the surface zone should be different for the different seasons (Jackson 1973). The soil water within the surface zone can be lost directly to the atmosphere via evaporation and indirectly via transpiration. This continuous process is called evapotranspiration (Moiwo and Tao 2015).

2.5 Measuring soil water content

The measurement of the water content of soil and the unsaturated zone is fundamental to irrigators and to investigations across a broad range of industries. As such, while a range of demands on measurement are required (Gardener et al. 2000), there are two common methods currently utilised, these are thermogravimetric and dielectric (by means of capacitance) and are described below.

2.5.1 Thermogravimetric method

The thermogravimetric method of measurement requires the removal of soil water by evaporation and is achieved by oven drying samples. This method is considered the most established and true direct measurement of soil water content (Smith and Mullins 2000; Charlesworth 2005) and is used as a standard for calibration of alternative soil moisture evaluation techniques (Zazueta and Xin 1994; Walker et al. 2004).

2.5.2 Capacitance probes

Indirect measurement techniques, such as dielectric methods do offer an alternative to the thermogravimetric method but they require careful calibration to convert the sensor response to soil moisture in different soils and temperature conditions (Cosh et al. 2005). Dielectric methods of soil measurement include capacitance techniques which are used to exploit the strong dependence of soil dielectric properties on water content (Smith and Mullins 2000).

Soil water content is determined by its effect on a dielectric constant by measuring the capacitance between two electrodes implanted in the soil (Zazueta and Xin 1994). By using appropriate calibration curves, the dielectric constant measurement can be directly related to soil moisture (Topp et al. 1980; Kennedy et al. 2003).

The dielectric constant is a measure of the capacity of a non-conducting material to transmit electromagnetic waves or pulses. The dielectric of dry soil is much lower than that of water, and small changes in the soils free water have large effects on the electromagnetic properties of the soil water media (Charlesworth 2005).

Where soil moisture is predominantly in the form of free water; for example, in sandy soils, the dielectric constant is directly proportional to the moisture content. The output from the sensor is not linear with water content and is influenced by soil type and soil temperature (Zazueta and Xin 1994).

The development of non-destructive capacitance probes allows continuous monitoring and recording of soil moisture (Villagarcía et al. 2004). Capacitance probes for soil water monitoring have been used broadly in natural resource management, including research on crop yield, watershed management, precision agriculture and irrigation scheduling (Hanson et al. 2004). In horticultural management, using capacitance probes with data-loggers allows near continuous measurement and observation of soil water content, as well short and long-term trends, such as plant daily water use (Starr et al. 2009). Importantly, they allow for the observation of irrigation water and rainfall penetration through the soil profile (Zekri et al. 1999).

In Kennedy et al. (2003), in-situ capacitance probes for measuring soil water content were found to offer three main advantages over other techniques, such as electrical resistance sensors, neutron probes and gravimetric sampling. They are: relatively low in cost compared to other in situ equipment, such as time–domain reflectometry (TDR systems); they require minimal maintenance; and they are relatively easy to install.

2.5.3 Capacitance probes and leaching

By knowing the soil moisture content (θ), irrigators can make timely decisions on starting and stopping water application which optimises water use and crop yield (Hanson et al. 2004). For example, Fares and Alva (2000) demonstrated that soil water monitoring using capacitance probes can also be used to determine drainage below the root zone. Arregui and Quemada (2006) also noted that probes were effective in determining the drainage volumes at depths of up to one metre using daily soil water measurements.

2.6 Soil water salinity

In horticulture, salinity problems occur if salts accumulate in the crop root zone at concentrations that result in a reduction or loss in yield. Plant available water is at its maximum and soil salinity is at its lowest concentration immediately after irrigation (Warrence et al. 2002). Under normal conditions, salts are added to the soil with each irrigation (Oster 1994). The crop removes most of the applied water from the soil to meet its evapotranspiration (ET) demand but leaves most of the salt behind to concentrate in the decreasing volume of soil water (Ayers and Westcot 1985). However in irrigated crops, salts often originate from either a saline, high water table or from salts in the applied water (Ayers and Westcot 1985; Lovell 2006).

A reduction in yield occurs when these salts accumulate in the root zone to such an extent that the crop is unable to extract sufficient water from the saline soil solution. If water uptake by the plant is appreciably reduced, the plant slows its rate of growth (Ayers and Westcot 1985; Schoups et al. 2005). This effect becomes most pronounced during periods of high evapotranspiration demand, such as hot sunny summer days and/or during the peak of the growing season (Warrence et al. 2002).

If there is no movement of water beyond the bottom of the root zone (known as leaching), the salt will accumulate and increase the concentration within the root zone (Oster 1994). Conversely, salt leaching can lead to salt build up in both shallow groundwater below the plant root zone and underlying aquifers (Schoups et al. 2005). Ayers and Westcot (1985) describe how a portion of the added salt must be leached from the root zone before the concentration affects crop yield. This is achieved by applying sufficient water so that a portion percolates through and below the entire root zone, carrying with it a portion of the accumulated salts (e.g. Figure 2-1).

Ezlit et al. (2010) attributed the source of salinity problems primarily to the quality of the irrigation water and the time required to develop an issue can be determined by the concentration of salts in the source water and associated management practices.

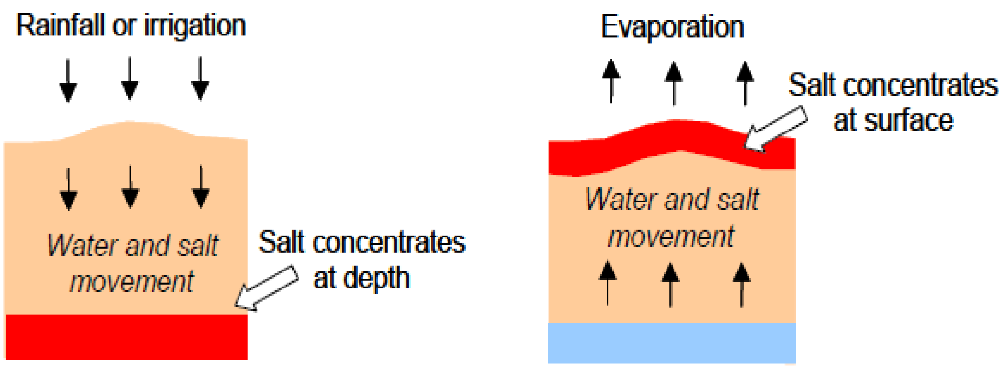

Figure 2-2: Illustration of typical salt distribution in the soil profile under overhead sprinkler application (after Cook et al. 2006).

2.6.1 Salinity effects

As noted above, salts accumulate in water and soils due to evaporation, transpiration and mineral dissolution. Salt in soil water reduces water availability by increasing the force the plant must exert to extract water, which induces water stress (Cook et al. 2006) and this additional force is referred to as the osmotic effect or osmotic potential. The osmotic effect is a natural process where water, passing through a semi permeable membrane, moves from a solution of low concentration to one with a higher salt level (Lantzke et al. 2007). The high concentration of salt in the soil water makes it harder for roots to absorb water from it, reducing the rate of water uptake by plants, even when there is sufficient water available (Ayers and Westcot 1985; Warrence et al. 2002). Growth is subsequently slowed and yields reduced. This effect is progressive and increases in proportion to the salinity (Flowers and Yeo 1989; Lovell 2006).

Toxicity problems will occur if certain constituents – predominantly sodium (Na^+) and chloride (Cl^-) ions - in the soil or soil water are taken up by the plant and accumulate to concentrations high enough to cause crop damage or reduced yields (Ayers and Westcot 1985; Grattan and Grieve 1999). Damage may result when these ions are taken up, either by the roots or by direct contact on the leaves. Ions absorbed by the roots are transported to the leaves where they accumulate during transpiration (Ayers and Westcot 1985; Lantzke et al. 2007). Under normal conditions, the roots of most plants exclude these salts during water uptake which concomitantly contributes to an increased concentration in the soil (Mass and Hoffman 1977).

Typical sodium toxicity symptoms are leaf burn, scorch and dead tissue along the outside edges of leaves, in contrast to the symptoms of chloride toxicity which normally occur initially at the extreme leaf tip (Lantzske et al. 2007). In addition, high concentrations of sodium in irrigation water can also induce plant calcium and potassium deficiencies in soils low in these nutrients.

In general, the effect of salinity is to reduce a plant’s growth rate, resulting in smaller leaves, shorter stature and sometimes fewer leaves (Shannon and Grieve 1999). Although salinity affects plants in many ways physiologically, adverse symptoms rarely occur except under extreme salinisation (Maas and Hoffmann 1977). The severity of salinity response can be affected by environmental interactions, such as relative humidity, temperature and radiation (Shannon et al. 1994).

2.6.2 Measuring salinity

Salinity is the presence of soluble salts in the soil solution which may be naturally occurring or derived from rainfall, mineral fertilisers or irrigation water (Rhoades et al. 1999; Lovell 2006). More specifically, ‘salinity’ usually describes the concentration of dissolved minerals measured as a unit of volume or weight (Rhoades et al. 1999).

In irrigation, salinity is generally described as total salts, irrespective of the constituents involved (Ezlit et al. 2010). The salinity of crop soil water is often reported as total salt concentration or total dissolved solids (TDS) which are the total amount of mobile charged ions, such as minerals, salts or metals dissolved in a given volume of water (Grattan 2002). This can be determined by evaporation of a known volume of water to dryness and weighing the quantity of dissolved material contained in that amount (Rhoades et al. 1999). TDS is expressed in parts per million (ppm) (Grattan 2002).

Another salinity measurement is electrical conductivity (EC) which is a numerical expression of the ability of a medium to carry an electrical current (Rhoades et al. 1999). Because the conductivity and total salt concentration of an aqueous solution are closely related, EC is commonly used as an expression of the TDS of an aqueous sample. EC measurements are based on the fact that the electrical current transmitted between two electrodes increases with an increase in soluble ionic salts, and vice versa (Grattan 2002). The basic unit of EC is the siemens per metre (S/m). In horticulture, EC is generally very low, so decisiemens is commonly used (dS/m).

Common methods for measuring soil water salinity include saturated paste extracts and soil suspension (Maas and Hoffman 1977; Shannon and Grieve 1999), such as:

- EC1:5 – the electrical conductivity of a 1:5 soil water suspension, used routinely in analyses.
- ECse – the electrical conductivity of the soil saturation extract, used for predicting plant response – commonly predicted from 1:5 and soil properties, or it can be measured directly (Maas and Hoffman 1977).

The EC1:5 soil water suspension method is the electrical conductivity of a 1:5 soil water suspension, which is used routinely in analyses (Rayment and Higginson 1992; Lovell 2006). In an Australian context, the ratio of 1:5 was established in response to difficulties when using the traditional saturation extract mixing method with heavy textured soils.

EC1:5 gives a different result than a saturated extract and tends to underestimate the electrical conductivity of sandy soils compared with clay soils (Rayment and Higginson 1992). This method, however, is relatively quick and inexpensive and is therefore appropriate for field tests. Field test results will differ from laboratory results because soil drying, shaking and settling times are not standardised in the field. However they are generally quite adequate for practical salinity appraisal purposes (Rhoades et al. 1999).

2.6.3 Salinity tolerance thresholds

A plant's salt tolerance is its inherent ability to withstand the effects of high salts in the root zone or on the plant's leaves without a significant adverse effect (Shannon and Grieve 1999). Not all plants respond to salinity in the same way and some crops can produce acceptable yields at a much greater soil salinity than others. (Ayers and Westcot 1985). Impacts on crop production can be described in terms of 'percentage yield loss' (Harvey and Strudwick 2009). Studies conducted by Biswas and colleagues (2009) to measure the effect of increasing soil salinity on crop yield, reported that yields appeared to remain constant up to a certain salinity value known as the 'threshold' and then begin to reduce.

Table 2-1 below provides a list of threshold values in Primary Industry and Resources South Australia (PIRSA 2006) expressed as the electrical conductivity of soil water (ECsw) for maximum production of horticultural crops and expected yield reductions from higher salinity levels.

Table 2-1: Soil water salinity thresholds for horticultural crops (PIRSA 2007).

Crop	Soil water salinity threshold (ECsw) in dS/m		
	0% yield loss	25% yield loss	50% yield
Orange	3.4	6.6	9.6
Grapefruit	3.4	6.6	9.6
Lemon	3.4	6.6	9.6
Apricot	3.2	5.2	7.4
Peach	3.4	5.8	8.2
Carrot	2.0	5.8	9.2
Onion	2.4	5.6	8.6
Potato	3.4	7.6	11.8
Tomato	5.0	10.0	15.0

2.7 Leaching

As noted above, leaching salts for the prevention of excessive salt accumulation in irrigated soils is essential for sustainable crop production (Barnard et al. 2010). It is achieved by applying sufficient water so that some of it percolates through and below the entire root zone carrying with it a quantity of the accumulated salts (Ayers and Westcot 1985; Monteleone and Libutti 2012).

Salt removal by leaching must equal or exceed the salt added by the applied water or the salts will accumulate at the root zone, eventually reaching concentrations prohibitive to crop yield. The amount of additional water needed to do this effectively is termed the 'leaching requirement' or 'fraction' (Ayers and Westcot 1985; Rhoades et al. 1999). Identifying the crop leaching requirement varies as to the irrigation method, crop type, geology and climatic condition (Ayers and Westcot 1976; Cardon et al. 2007).

There are, however, limitations to leaching. With high evaporative conditions, it is difficult for irrigators to supply the required crop water and leaching water during the summer. Ayers and Westcot (1976) noted that effective leaching should be carried out at pre-planting, as most crops are more susceptible to salt damage during germination or in the seedling stages.

Leaching can also be conducted on a limited basis at times during the growing season when a grower may have high quality water available (Cardon et al. 2007). Alternatively in situations where a grower has numerous water sources of varying quality, leaching can be achieved through planned events at times when salinity is known to cause stress for a given crop (Lantzke and Calder 2004; Cardon et al. 2007).

Comparing the leaching requirement to irrigation efficiency is critical for sustainable irrigation practices and Meyer and Bowmer (2004) note that many growers are attuned to the balance in the application of water. Sustainability, therefore, requires the ability to consider a variety of factors, including soil geology, groundwater and climatic conditions.

2.7.1 Rainfall – natural leaching

Rainfall is considered the primary source of water for horticulture and agriculture globally (Dastane 1978) and it generally has salinity less than that of applied water. In irrigated soils, root zone salinity largely depends on a number of factors, including but not limited to, annual rainfall (Cook et al. 2006; Platts and Grismer 2014). Monteleone and Libutti (2012) evaluated the capability of yearly rainfall to leach salts accumulated in the soil during the previous spring–summer irrigation season in Mediterranean climates. While the research was conducted under simulated conditions, it concluded that annual cultivation of a spring–summer irrigated crop without any additional leaching (including rainfall) leads to a saline build up.

Platts and Grismer (2014) concluded that rainfall was critical for sustainable irrigation and found that effective leaching of crop root zone salinity occurs during the winter rainy season, when ET rates are generally low. Dastane (1978) explains by way of illustration (Figure 2-3), that a certain fraction of rainfall lost beyond the root zone is considered essential for the rinsing of salts, especially in arid and semi-arid regions.

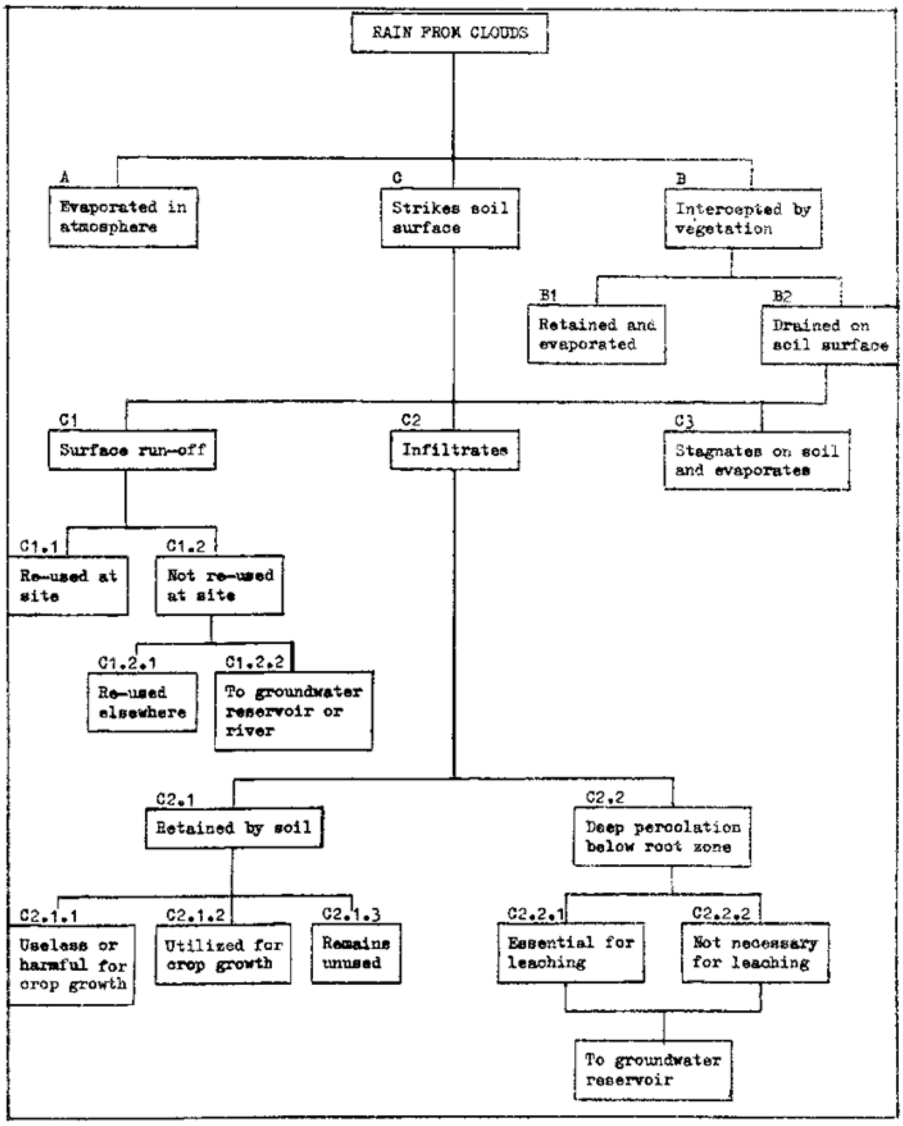

Figure 2-3: The pathway of rainfall (Source: Dastane 1978).

2.8 Conclusions

Sustainable irrigated horticulture relies on maintaining sufficient soil water content at the crop root zone. However, salts are known to accumulate within the soils as a result of irrigators managing soil water and limiting the drainage of applied water past the crop root.

Thermogravimetric and dielectric methods are used to obtain accurate soil water content measurements. The use of multisensory capacitance probes is sufficient to monitor and measure soil water content. The capacitance probes are capable of providing qualitative data which can determine the movement of applied water and rainfall through the soil profile.

Soil salinity is known to be prohibitive to crop yield at high concentrations. Soil salinity can be measured in field and is known to be greatest during periods of high ET demand. Soil salinity can be effectively managed by leaching, which requires the application of surplus water volumes. While ET is low, winter rainfall can be effective in rinsing salts accumulated from summer irrigated crops, especially in Mediterranean climates.

CHAPTER 3. PHYSICAL CHARACTERISTICS OF THE HORTICULTURAL SITE

3.1 Site selection

The research investigations were conducted at a 300 hectare horticultural lot of irrigated land on which vegetable crops are grown in year-round rotation. The property is owned by Coast Pastoral Property Pty Ltd. and operated by Beta Farms Pty Ltd. It is located approximately two kilometres inland from the coast, near Binningup, 120 kilometres south of Perth on the western edge of the Swan Coastal Plain (Figure 1-2).

3.1.1 Study site overview

Horticulture was initiated at this site in 2004 and has been substantially expanded since 2008. The water is extracted from three large ponds (W1, W2 and W3) that were excavated 3 to 4 m into the water table (Figure 3-1). The Coastal Limestone within which they are built enables the ponds to retain a box-shaped configuration below the water table and allows water to be drawn preferentially from the surface layer of the aquifer.

Pond W1 has been a water source since the beginning of the horticultural operation and is in the middle of an area that has been cropped annually since 2002. It provides good quality irrigation water in the surface three metres and is homogenous in salinity profile.

Water quality between the three ponds has been shown to vary and it is thought the reason for this is that the land had previously been cleared, planted and harvested using a 15-year crop of Tasmanian blue gum. As a result, the upper levels of the aquifer were modified by high evapotranspiration which would have varied with intensity over the area currently used for horticulture.

Pumping is via large direct-drive diesel pumps, the property presently has a licence to draw 2,100,000 m^3 of water per year and this occurs predominately in the period between November and April.

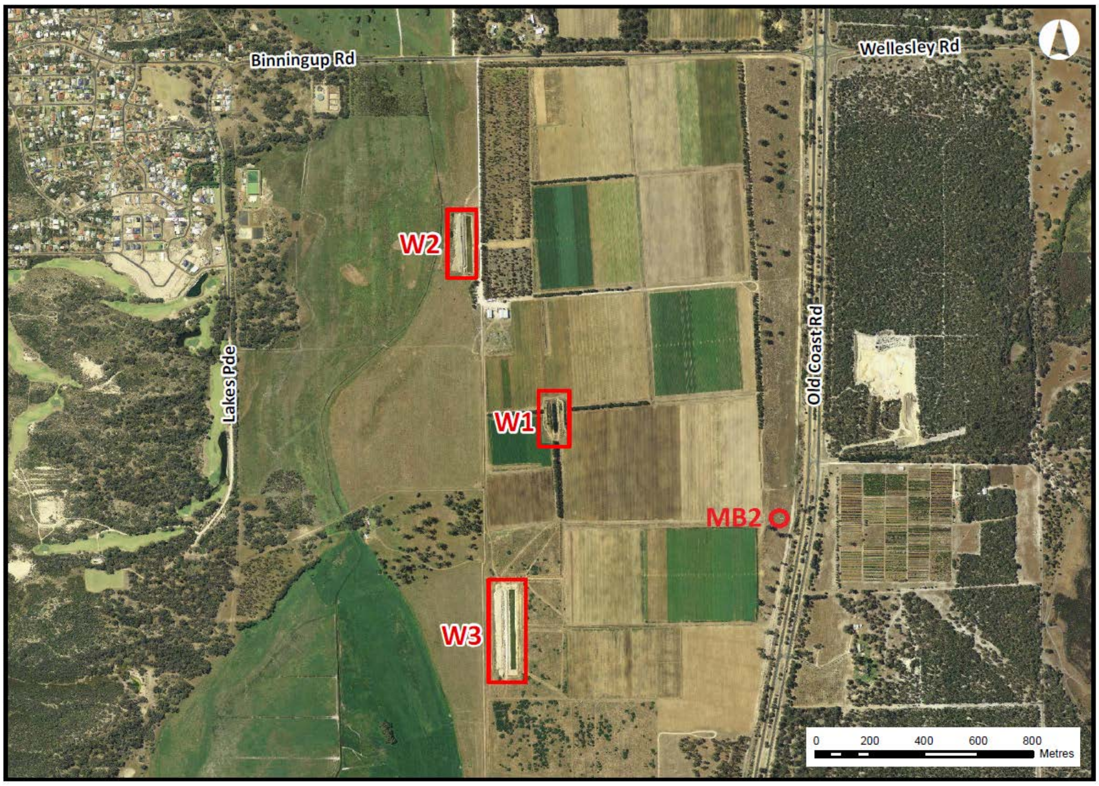

Figure 3-1: The three ponds W1, W2 and W3 from which irrigation water is extracted. Monitoring bore MB2 is also shown.

Work by Meagher (2010) indicated that the vegetable crops used an average of between 10,000–13,000 m^3 of water per hectare, approximating between 8.5 mm and 11 mm per day for a 17-week summer crop and is consistent with the intended 12 mm per day application for mid-to-late stages of a crop (M. Dell'Agostino pers. comm.)

The property has four monitoring bores and is adjacent to an array of long-term monitoring wells on Binningup Road managed by the Department of Water, Western Australia (DoW). Monitoring bore two (MB2), shown in Figure 3-1, is located on the eastern boundary of the property and, due to the small horizontal east to west hydraulic gradient (Smith and Hick 2001), it provides an indication of the underlying aquifer's water quality before it passes below the property.

Consistent differences in water salinity exist between the three ponds on the property, although the three are separated by 1.2 kilometres in distance running north to south. Pond W1 is 550 m from both W2 and W3. The proximity of Coastal Limestone to the surface and the shallow groundwater gives the leached solutes the ability to rinse away to the underlying aquifer which, under the increased hydraulic gradients experienced in the winter months, may be transported from the vegetable crop.

The property is six kilometres south of the Myalup agricultural weather station that provides both historical and real-time data on the full array of weather detail relevant to horticulture. The Bunbury Port Authority maintains a detailed oceanographic station, monitoring tide, sea level, water temperature and wind velocity.

The horticulture operators maintain accurate records of water use from each pond, together with fertiliser and chemicals application to crops. Thus, the property is set out in a configuration that is similar to a large-scale laboratory experiment, with appropriate test situations and controls.

3.2 Climate

The climate of the area is Mediterranean, where summer months provide hot dry conditions and the winters are wet and cool. While the climate of the region is well known, it was the weather and rain events that were of particular importance to this research. Observations recorded at the Myalup automatic weather station maintained by the Department of Food and Agriculture Western Australia (DAFWA) were used in this investigation and Figure 3-3 to Figure 3-7 present average annual rainfall, daily rainfall, daily minimum and maximum temperatures, solar radiation, pan evaporation and mean wind speed are presented for 2011 respectively. There was above average annual rainfall for the investigation year in comparison to the previous year (2010), which recorded 50 per cent less rain over more rain days (Figure 3-2).

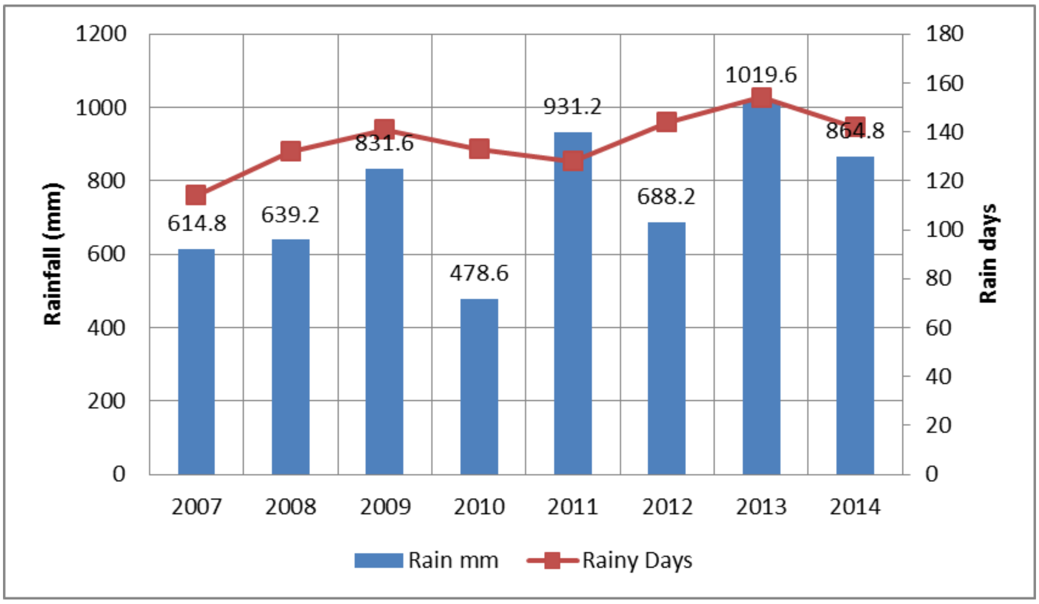

Figure 3-2: Myalup average annual rainfall compared to rain days (DAFWA 2015c).

Figure 3-3 presents the daily rainfall data indicating the number of rainfall events at greater than 30 mm. Rainfall events during the summer months are defined.

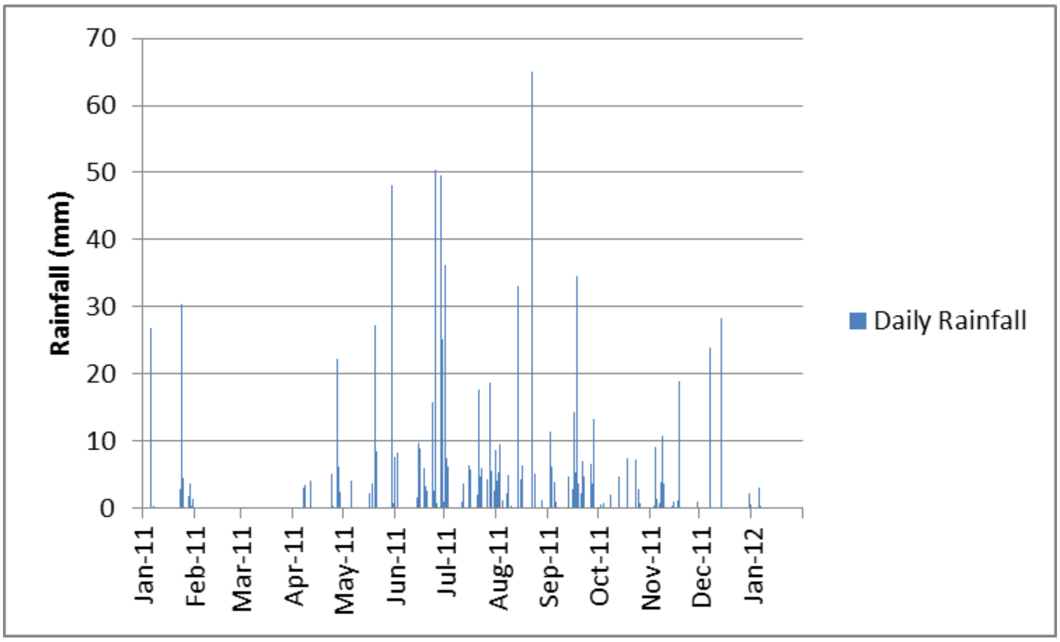

Figure 3-3: Myalup daily rainfall for 2011.

Figure 3-4 shows the comparison of summer and winter temperatures characterised by the Mediterranean climate. This trend is further demonstrated in the following graphs.

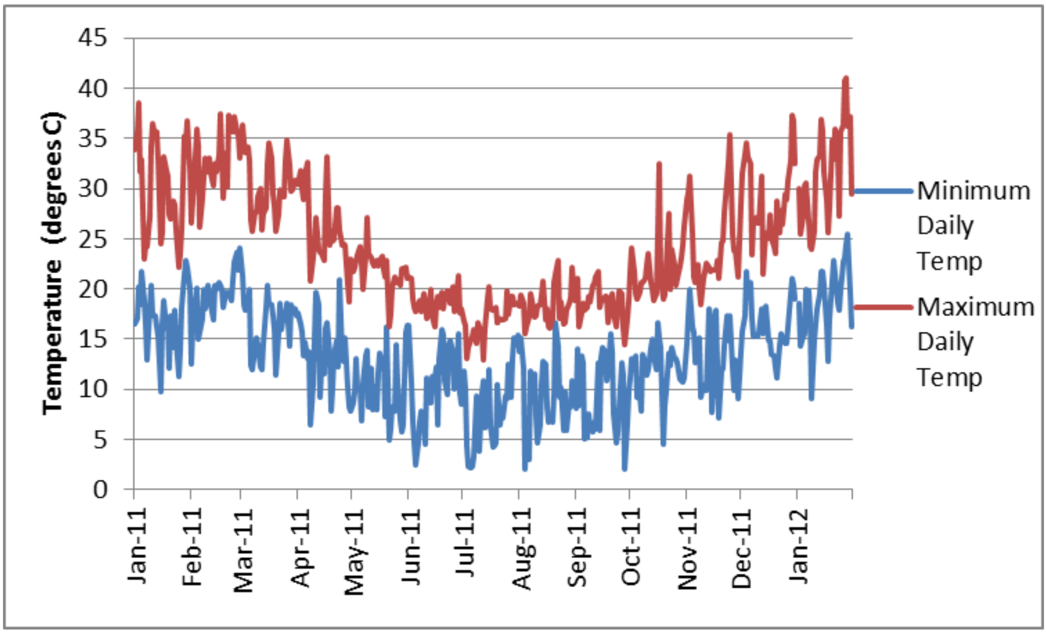

Figure 3-4: Daily maximum and minimum temperatures for 2011.

Figure 3-5 shows the effect of solar radiation during the summer period as a contributor to high summer evaporation rates.

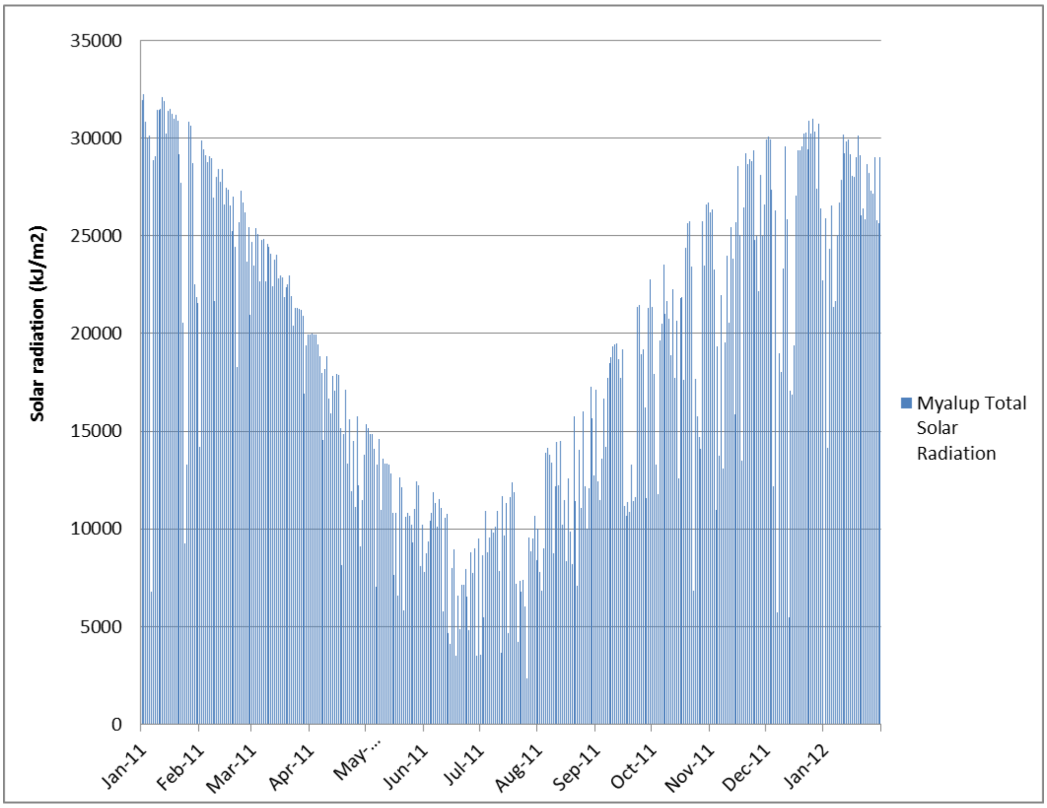

Figure 3-5: Total solar radiation for 2011.

There were extreme differences in evaporation rates between the summer and winter months and pan evaporation ranged from 0.6 mm in winter to 11.9 mm in summer (Figure 3-6).

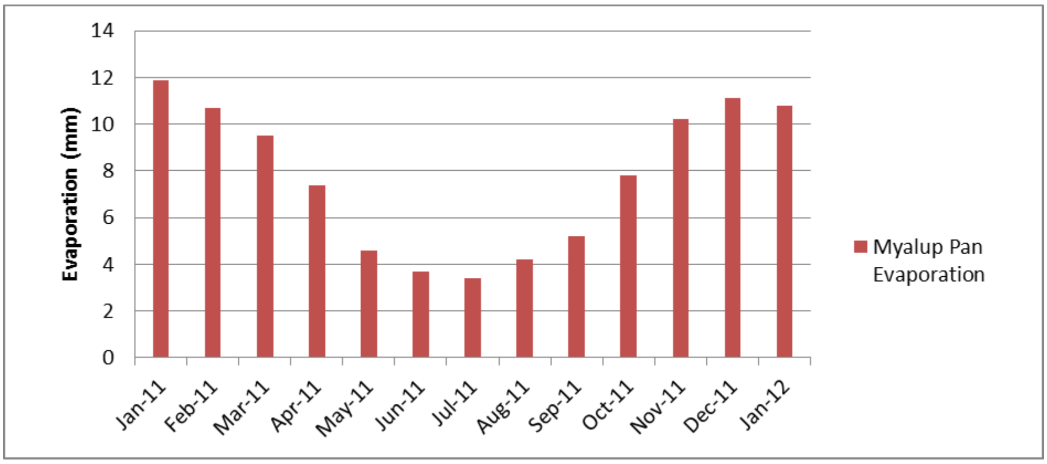

Figure 3-6: Annual pan evaporation for 2011.

Wind patterns for the summer months included easterly winds during the morning and south-westerly sea breezes during the afternoon (Figure 3-7). Winds during the winter months were observed to be associated with frontal systems and were variable in direction.

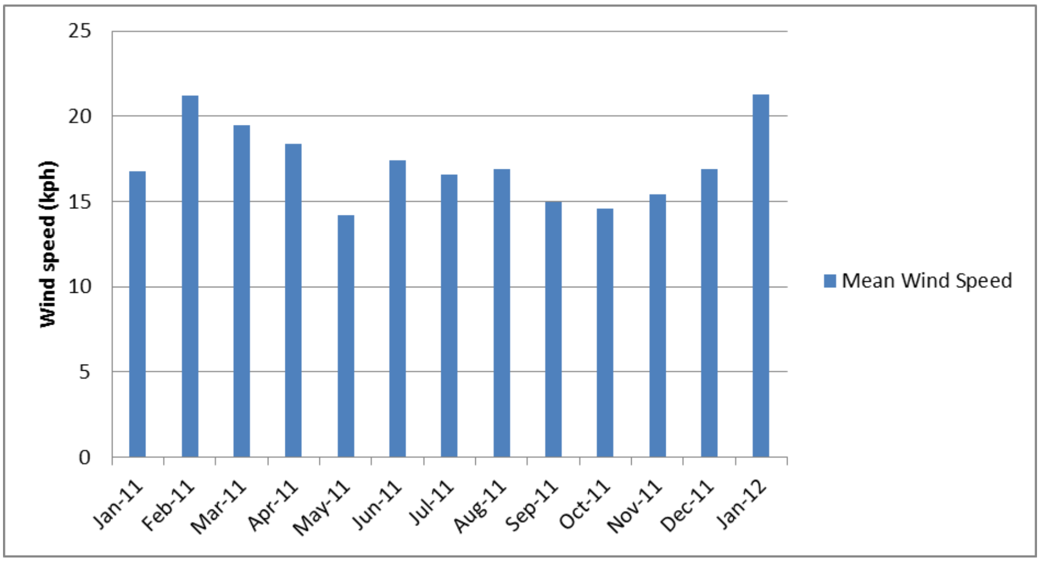

Figure 3-7: Mean wind speed for 2011.

In conclusion, the annual weather observations provided illustrate the Mediterranean climate and in particular, the high temperature, low humidity and high evapotranspiration conditions of the summer.

3.3 Geology

The geology of the area is well described by Rockwater Pty Ltd. (2009) in a hydrogeology study from Dawesville to Binningup which states:

"The Quaternary to early-Tertiary formations in the area have been informally termed the superficial formations (Commander 1988) and this terminology is used here. The entire section of the superficial formations has previously been referred to [as] the Tamala Limestone and, at the surface along the coast, the Safety Bay Sand. However, Semeniuk (1995) has redefined the stratigraphy of the upper part of the Pleistocene and Holocene section in the Yalgorup Plain area. For convenience, these new units are herein included as part of the superficial formations. This work has provided detail which describes complex lithological sequences. The lower part of the superficial formations remains undifferentiated under Semeniuk's (1995) scheme and the previous terms, Tamala Limestone and Ascot Formation, have been retained here for this section. The available lithological data are not as detailed for the lower part of superficial formations as for the upper part in the study area" (p. 5).

Limestones, sands, karst surfaces, and calcretes underlying the Mandurah-Eaton Ridge, the Yalgorup Plain, and the Quindalup Dunes of the Leschenault-Preston barrier (Figure 3-8) form the hydrological framework of the area, with major intake zones (recharge zones) influenced by the occurrence of quartz sand formations, and pipe-punctured limestone, and the transmissivity of the Pleistocene formations determined/influenced by the limestone grainsize, amount of cementation, calcretisation, occurrence of calcrete sheets, and macrokarst and microkarst development (Semeniuk 1997).

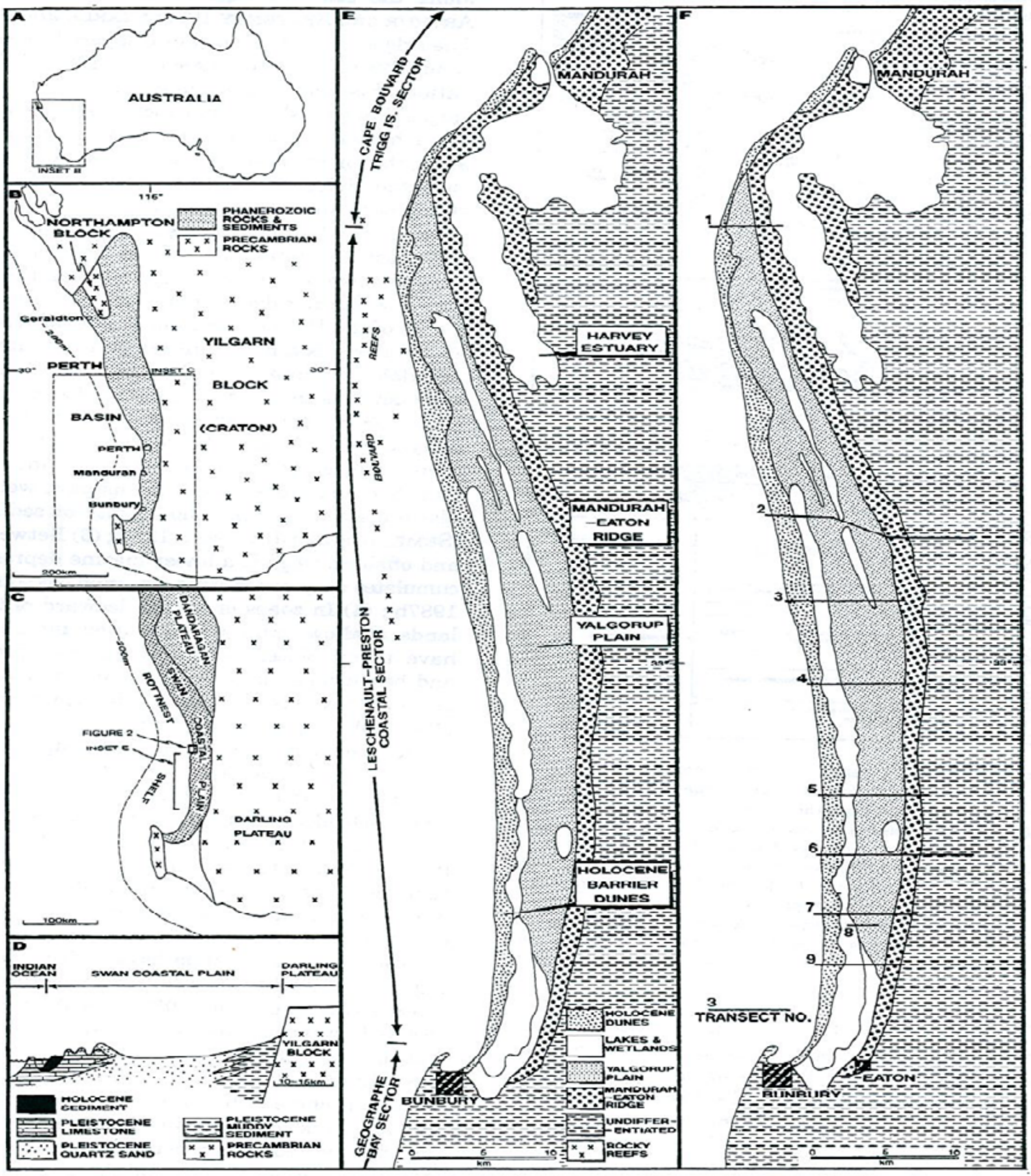

Figure 3-8: Regional geology and geomorphology (Semeniuk 1997).

Semeniuk (1995) noted that Pleistocene limestones and quartz sand form distinct tracts of terrain on the Yalgorup Plain. Previously, the limestone units in this area were referred to as the Tamala Limestone, but they can be identified as distinct units by their lithology, stratigraphy and geography. This author also noted that they are lithologically distinct from the Tamala Limestone at its original location, at its type section, and from the calcarenitic aeolianite regarded as Tamala Limestone in the central Swan Coastal Plain of the Perth regional area.

The research location predominantly overlies the upward shoaling limestone system referred to as the Kooallup Limestone that underlies a Pleistocene landform termed Kooallupland (Semeniuk 1995).

3.4 Soil

The Spearwood sands of the Spearwood dune system occur on the western slopes of the Cottesloe Association at the junction with landscape developed on marine limestone (Yoongarillup Association). The Spearwood dune system is generally described as comprising two soil associations, the Cottesloe (to the west) and Karrakatta (to the east) (Bolland 1998; McArthur 2004).

Eroded sand was blown inland, which exposed the darker coloured sand (Cottesloe) and limestone as described by Bolland (1998), who concluded that the multitude of names used for the sands of the Spearwood dune system, including Cottesloe and Karrakatta, has led to confusion. The sandy yellow soils within the Spearwood dune system, including those of the Karrakatta association, are commonly referred to as Spearwood sands (Rowe et al. 2017) and will be used to refer to the yellow and brown sands overlying the coastal limestone within 1.5 m of the surface.

Soils at the research location are characterised as shallow to moderately deep siliceous yellow-brown sands with minor limestone outcrop and are therefore referred to here as Spearwood sands for the purpose of characterising their physical and chemical properties. The soils are fine to medium sands with a weak to very weak consistence and single grain structure.

The Spearwood sands overlies the coastal limestone and varies in thickness from 0.5 to 2.5 m. Shallow soils of < 30 cm are common when associated with limestone outcrops, as is experienced in some parts of the property not used for irrigated horticulture.

The soil profile description (Table 3-1) with physical and chemical analyses of Spearwood sands (Table 3-2) is consistent with soil mapping (McArthur 2004; Rowe et al. 2017).

Table 3-1: Description of the typical soil profile at the research site

Horizon	Depth (cm)	Description
A	0-30	Dark Brown, loamy fine sand, dry
B	30 – 50>100	Strong brown, loamy fine sand, moist soil
R	50>100 +	Limestone rock

Table 3-2: Physical and chemical analyses of Spearwood sands after Rowe et al. (2017)

Sample depth (cm)	**Particle size (%)**				**pH**		**EC dS/m**	**OC %**	**$CaCO_3$ %**
	CS	MS	FS	<0.075mm	$H_2$0	$CaCl_2$			
0-30	9	43	40	8	8.4	7.8	8	.77	3.3
30-100	6	35	53	3	8.3	7.4	3	.38	0.6

A cross-section of the soil (Figure 3-9) indicates that the surface 25–30 cm of topsoil, in which the crops are grown, is dark-coloured and humic. It has a loamy sand texture and is typical for topsoils with organic material present (Rowe et al. 2017).

While the change in colour is consistent with soil data for the local area, the sharp contrast of the interface is believed to be representative of an artificial source, in this case tilling of cover crops by tractor-drawn rotary hoe or cultivator. Cover crops of oats and legumes are grown between crops on the property and are subsequently ploughed in to the observed depth (M. Dell'Agostino pers. comm.). The karst calcarenite hosts the superficial aquifer used on site and is illustrated in Figure 3-10.

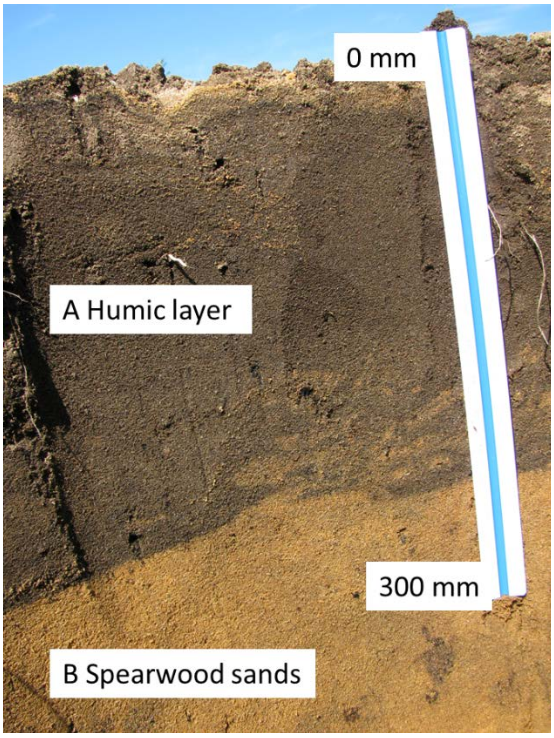

Figure 3-9: Interface of the tilled crop soil and undisturbed Spearwood sands at approximately 30 cm below the surface.

Figure 3-10: Cross-section of the soil and karst calcarenite layer from one of the irrigation ponds.

3.5 Superficial aquifer

The quaternary deposits, along with tertiary accumulations are known locally as the superficial formations and, when saturated, form an unconfined aquifer system termed the ‘Superficial Aquifer’ (Smith and Hick 2001). The local components of the

Coastal Limestone aquifer are depleted by a combination of leakage through the shoreline, to local inlets and the occasional river system, plus in-situ evapotranspiration of indigenous phreatophytic vegetation (Commander 1988).

The aquifer is known to become more saline at depth (Commander 1988) and high-volume bores tend to draw it down and mix in more saline water. Occasionally salinity levels are found to inhibit or preclude sprinkler irrigation.

The thickness of the unconfined Coastal Limestone aquifer beneath the study site is known to be 14–20 m thick and have a heterogenic porosity of approximately 40 per cent (Commander 1988; Rockwater Pty Ltd. 2000). The coastal strip of the superficial aquifer is characterised by very high transmissivity, due to the secondary porosity in the Coastal Limestone, and is generally associated with small horizontal east-to-west hydraulic gradients (Smith and Hick 2001). Thus, although the aquifer is regionally contiguous, it can be anticipated to have local preferential channelling of groundwater flow. Steeper horizontal hydraulic gradients have however been identified in hydrogeological logs from monitoring bores taken from the Department of Water immediately north of the study site running east to west, along Binningup Road.

The superficial aquifer contained in the Coastal Limestone occurs along the coast of Western Australia from Geraldton to Bunbury. It is constrained to the west by seawater intrusion and unconstrained to the east. It is replenished by a combination of in situ rainfall and groundwater migration from an extension of the aquifer in sandy soils to the east.

Results in Meagher 2010, indicate groundwater movement very different to modelling previously conducted by Rockwater Pty Ltd. (2000; Figure 3-11) on the site. The migration rate of groundwater observed below the property was found to be such that the ponds can be rinsed completely on a daily basis, without any pumping.

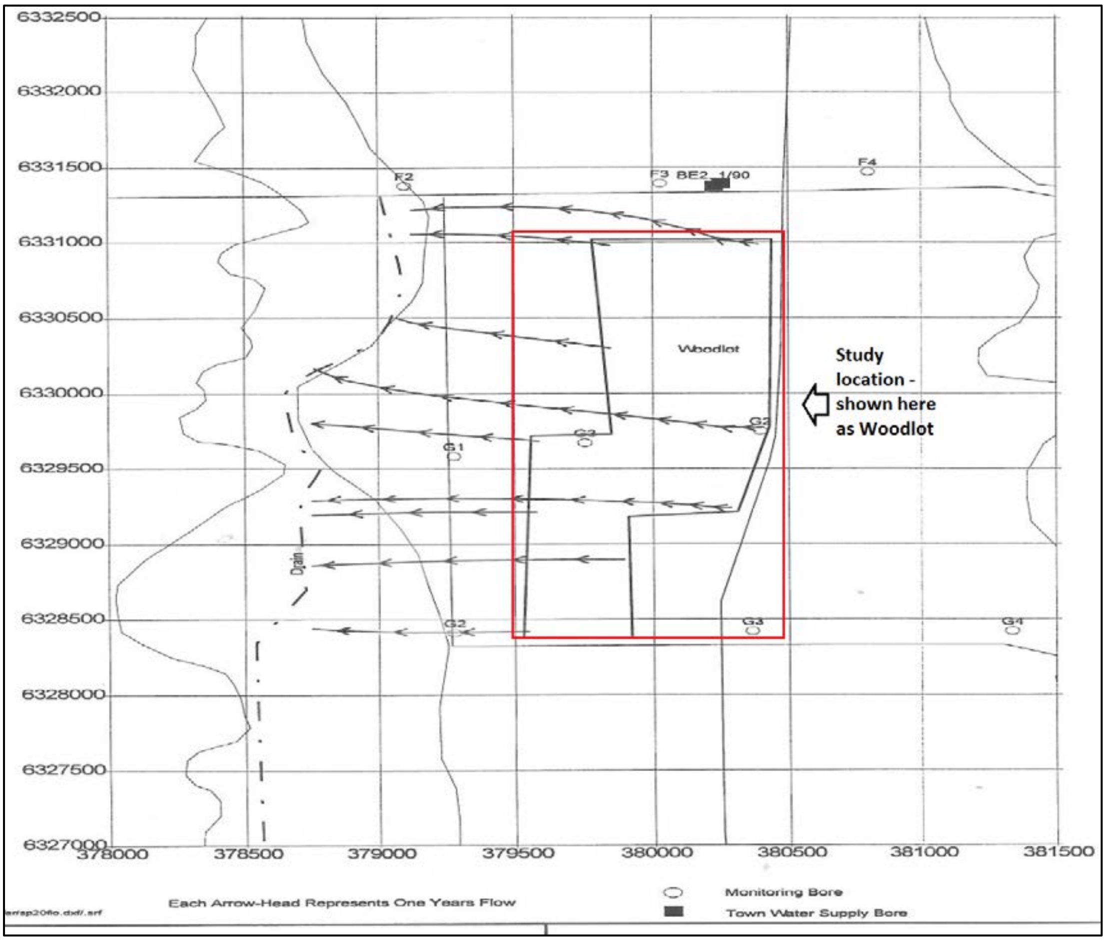

Figure 3-11: Modelling by Rockwater Pty Ltd. showing predicted groundwater flow underneath the research location (Rockwater Pty Ltd. 2000).

3.6 Horticulture

The vegetable crops grown at the horticultural property are predominately potatoes and carrots, with occasional onions. It is during the eight month, non-winter period that large volumes of water are extracted from the underlying, but near-surface aquifer (referred to as the superficial aquifer) and applied to the crops by overhead sprinkler irrigation.

In addition to the climate and soil structure in the region, the availability of water and TDS levels have a significant effect on horticulture. Without conditioning, the soils are not fertile and are subject to rapid drying (Bolland 1998). The grower’s condition the soil by planting cover crops, such as wheat, oats or lupins, then ploughing the crop in while green (M. Dell’Agostino pers. comm.). This leads to local composting and a build-up of humic material in the soil profile. The remnants of vegetable crops are similarly ploughed in. In carrot crops, this is substantial, because leaves are stripped and turned into the soil during the harvesting process

3.6.1 Crop fertiliser

The property's infertile soils necessitate that large quantities of fertiliser are applied to crops. Average application rates are approximate to industry standards (as described in Meagher (2010)) and accurate records are maintained by the operators pursuant to their license conditions.

A suite of fertilisers appropriate for different stages of crop development are applied and contain large quantities of the major nutrients nitrogen (N), phosphorous (P) and potassium (K), moderate amounts of calcium (Ca) and magnesium (Mg), and small quantities of trace elements.

The types of fertilisers typically applied include NPK (nitrogen, phosphorous, potassium formula), K-Mag (potassium with magnesium and sulphur), sulphate of potash (SOP), ammonium nitrate (AN), mono-ammonium phosphate (MAP), Hi-trace (trace elements) and boron (B). Methods used to distribute the fertiliser include banding, boom spraying and fertigation via the overhead sprinklers system. The total elements applied to a typical crop from planting to harvesting are shown in Table 3-3.

Table 3-3: Quantities of elements applied to crops via fertilisation.

Element	Quantity (L or kg/ha)
Nitrogen (N)	265
Phosphorous (P)	170
Potassium (K)	631
Calcium (Ca)	14
Magnesium (Mg)	55
Iron (Fe)	0.8
Manganese (Mn)	0.65
Copper (Cu)	0.3
Zinc (Zn)	0.4
Boron (B)	1.7
Molybdenum (Mo)	0.1

Overall application of fertiliser is relatively constant and varied between 43,000 to 47,000 kg in the years preceding the research period. Total nitrogen application rate was recorded between 525 kg/Ha to 433 kg/Ha. Records of individual fertilisers and fungicides, herbicides and insecticides are also applied during the crop growth when required and records maintained by the horticultural managers.

3.7 Groundwater quality

Groundwater quality at the horticultural site is described in Meagher (2010) and TDS and nitrogen from samples taken at MB2 and pond W1 are provided in that report, where he describes the groundwater quality at MB2 as pristine and of low salinity (200–300 ppm) and nitrogen (<0.5 ppm).

Results at W1 show that an average TDS of 800 ppm was maintained for the monitoring period (2002–2010) and that nitrogen varied sporadically up to 5.8 ppm (Meagher 2010). It is well known that leached nitrogen enters the water table beneath vegetable crops on the Swan Coastal Plain. Long term TDS and nitrogen values are provided in Figure 3-12 and Figure 3-13 respectively (Meagher 2010).

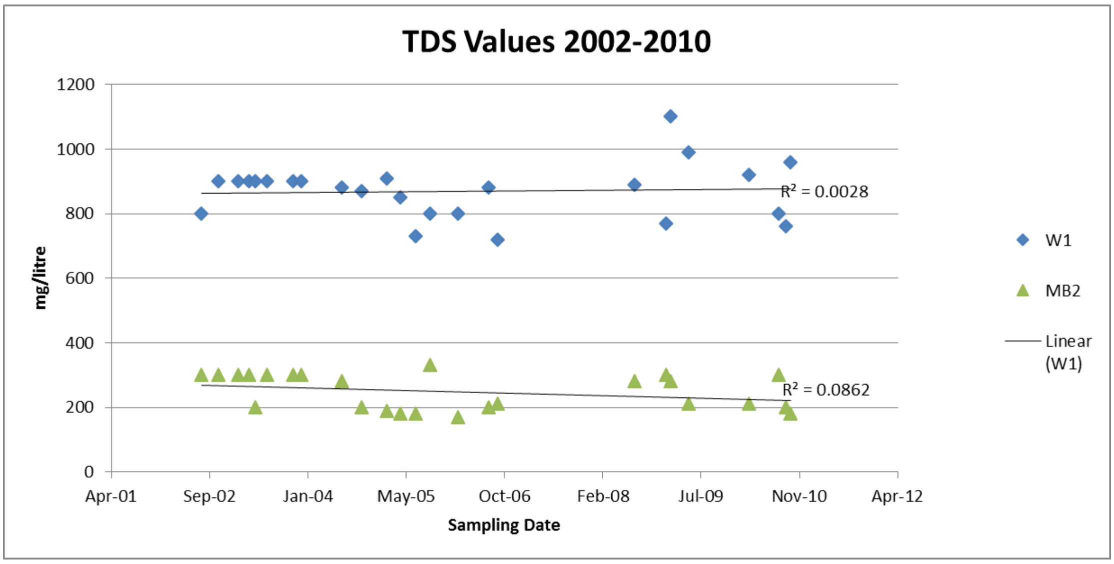

Figure 3-12: TDS values for W1 and MB2 from 2002-2010.

Figure 3-12 includes a regression line indicating that TDS levels at both W1 and MB2 have remained relatively constant over the eight year monitoring period.

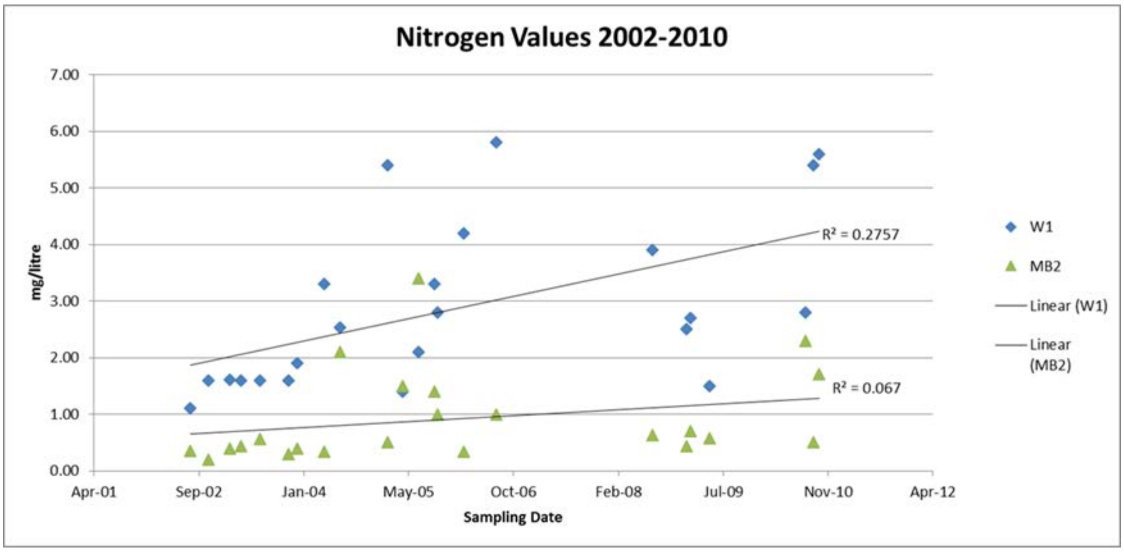

Figure 3-13: Nitrogen values for W1 and MB2 from 2002-2010.

The nitrogen value in W1 has fluctuated widely over the eight year monitoring period (Figure 3-14) in contrast to TDS, which has remained consistent at 800 ppm with minor seasonal variation. There is a similar, but less conspicuous, trend in the MB2 data. The occasional high MB2 nitrogen values in 2002–2004 were most likely due to nitrogen input from another property to the east of the horticultural site.

The conclusion is that while there is some inevitable rinsing of nitrate and other salts to the surface of the aquifer, infiltration and translocation of rainfall is sufficient to maintain the basic water quality for sprinkler horticulture and thus the sustainability of the practice. For example, the gradual rise and plateau of TDS in W2 and W3 is more likely to have occurred from heavy drawdown, taking water from the western side of the ponds, where the TDS is known to be higher - rather than from elevation due to sprinkler irrigation to the east of the ponds.

3.7.1 Chemical composition

Pursuant to licence conditions, horticultural managers are required to obtain regular water analyses for reporting purposes. The chemical composition of the groundwater at W1, W2, W3 and MB2 (refer Figure 3-1) presented in Table 3-3 provides an analysis of irrigation source water samples at the commencement of the research project.

Table 3-3: Groundwater chemical analysis at 08.02.2011.

Sample code	pH	EC 25°	TDS g/L < 0.05	Chloride mg/L <1	Sulfate mg/L <1	Orthophosphate –P ug/P/L <2	NO_3 +NO_2 ug.N/L <2	Total P ug.P/L <5	Total N ug.N/L <50
W1	7.6	1.3	0.83	140	310	14	3900	20	4400
W2	7.8	1.8	1.2	240	400	16	300	23	240
W3	7.7	1.3	0.78	180	140	18	<2	25	290
MB 2	7.3	0.3	0.23	23	60	22	140	69	710

3.7.2 Water use

There was extreme seasonal variation in water use on the property at the research location (Figure 3-14 and Figure 3-15). There was also a marked short-term variation in water application during the summer period. This variation, in part, reflects the area and age of crops during summer. Predominantly however it was due to extreme weather conditions (i.e. high temperature, low humidity and strong winds).

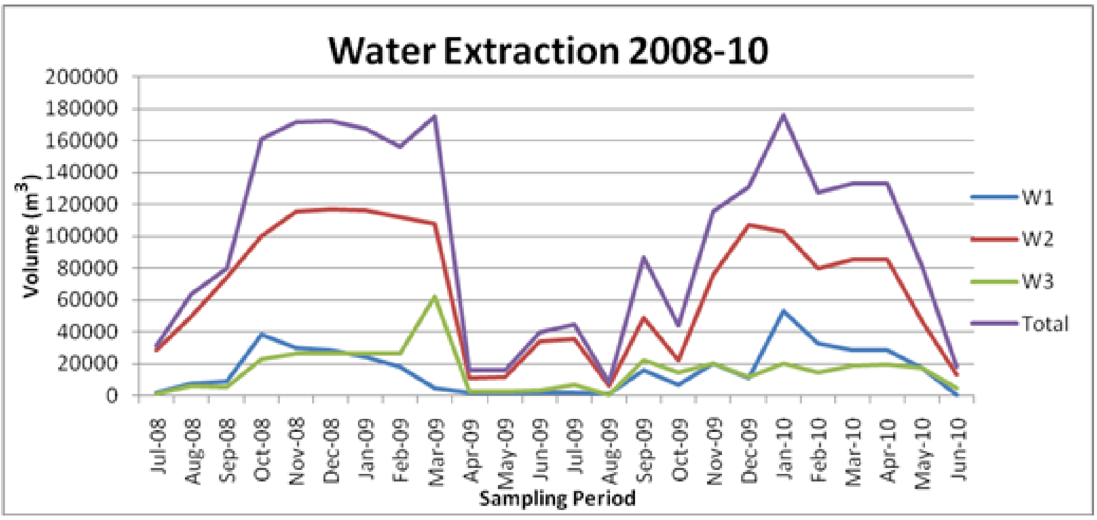

Figure 3-14: Volumes of water extracted between 2008 and 2010 (Meagher 2010).

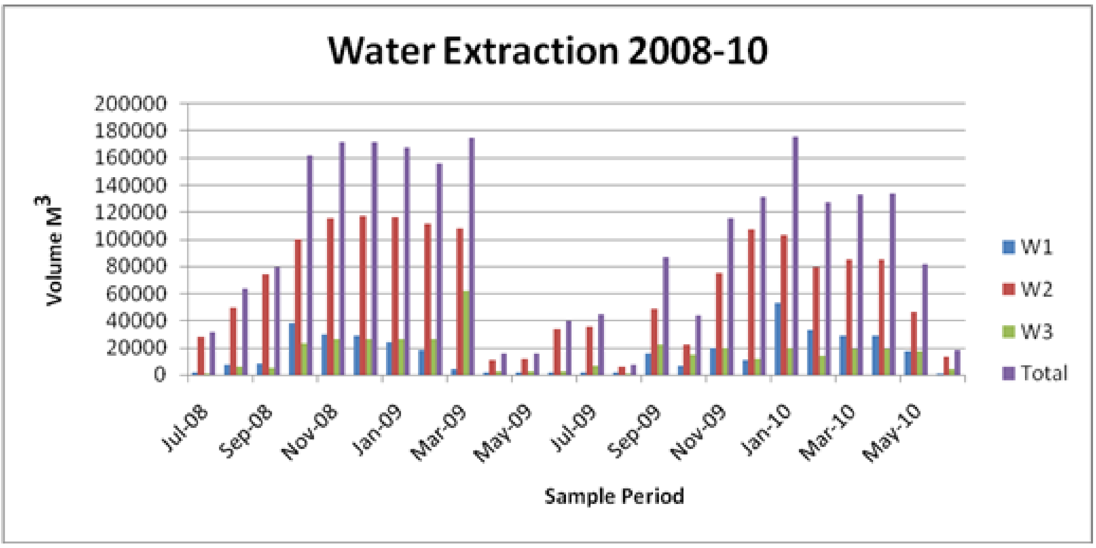

Figure 3-15: Volumes of water extracted between 2008 and 2010 (Meagher 2010).

Table 3-3 presents the volume of water extracted, in litres per month, at the property in the research location during the winter and summer periods, and illustrates the vast quantity of water required during the summer growing period.

Table 3-4: Historical records of water extracted (litres per month) (Meagher 2010).

Date	W1	W2	W3	Total
30/07/2008	2,058	28,221	1,130	31,409
30/08/2008	7,730	49,554	6,409	63,693
30/09/2008	8,630	74,309	5,260	79,569
30/10/2008	38,579	99,909	22,987	161,475
30/11/2008	30,242	115,419	26,262	171,923
30/12/2008	28,745	116,992	26,262	172,006
30/01/2009	24,550	116,477	26,262	167,289
28/02/2009	18,106	111,727	26,262	156,095
30/03/2009	4,503	108,127	62,266	175,396
30/04/2009	1,930	11,358	2,563	15,851
30/05/2009	1,623	12,061	2,564	16,248
30/06/2009	1,854	34,454	3,172	39,480
	168,550	878,608	211,399	1,250,434
Date	**W1**	**W2**	**W3**	**Total**

30/07/2009	1,854	35,484	7,093	44,431
30/08/2009	1,556	6,000	347	7,903
30/09/2009	15,986	48,586	22,297	86,869
30/10/2009	7,130	22,231	14,733	44,094
30/11/2009	20,034	75,650	20,098	115,789
30/12/2009	11,148	107,467	11,709	130,924
30/01/2010	53,028	103,123	20,055	176,206
28/02/2010	33,054	79,673	14,480	127,207
30/03/2010	28,895	85,160	18,957	133,012
30/04/2010	28,896	85,241	19,258	133,395
30/05/2010	17,444	46,565	17,479	81,488
30/06/2010	529	13,394	4,416	18,339
	219,554	708,574	170,922	1,099,657

Approximately 1,000 mm of sprinkler water is applied to each area of crop in addition to the average rainfall of 800 mm (Figure 3-16).

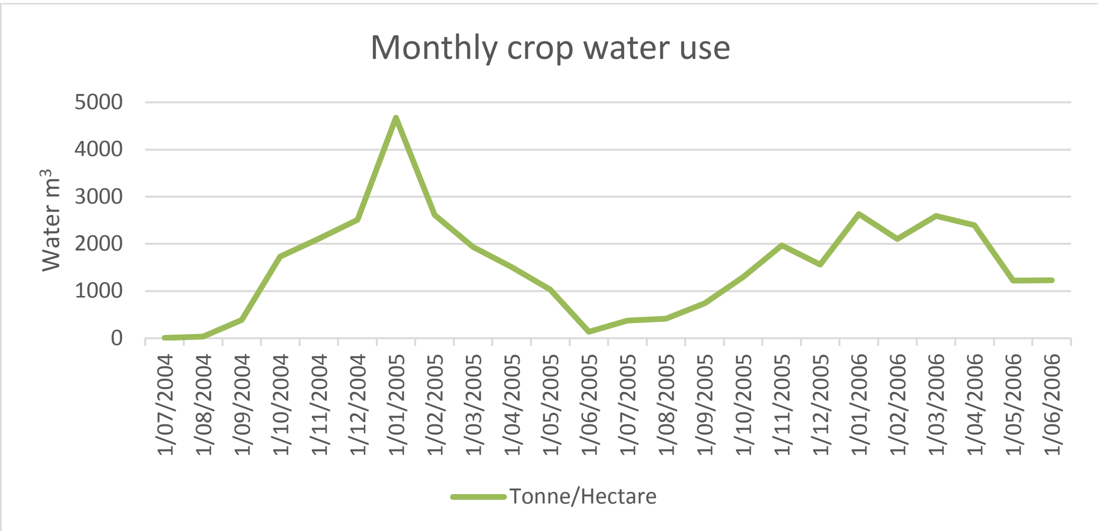

Figure 3-16: Monthly crop water use in tonnes per hectare.

3.8 Evaporative conditions

Overseas experimental studies on sprinkler irrigation have reported losses up to 45 % of the applied water through evaporation (Bavi et al. 2009; Uddin et al. 2014) however studies by Naughton (2009) have shown that evaporative losses at the sprinkler head during the peak summer period can range from between 25 and 40 per cent. This is as a result of occasional meteorological conditions at Binningup, such as high temperatures, high wind and high solar radiation, coupled with low humidity.

CHAPTER 4. METHODS AND MATERIALS

The investigation site at Binningup was chosen because of the nearby automatic, online weather station at Myalup maintained by the Department of Agriculture and Food, Western Australia (DAFWA), together with having a substantial history of groundwater measurements on and adjacent to the site.

4.1 Myalup weather station

This agricultural facility is situated 6.5 km north of the horticultural property under investigation at Myalup (33°5.695S, 115°43.136E) at an altitude 10 m and at the same distance from the coast. Operated by DAFWA, it provides real time and historical weather data for the immediate area including:

- air temperature
- relative humidity
- rainfall
- pan evaporation
- wind speed and direction
- soil temperature
- solar radiation (W/m^2).

Reference evapotranspiration is also available through the automatic weather station.

The tipping bucket rain gauges employed in this research did not distinguish between sprinkler water and rainfall so subtraction of Myalup rainfall data from the tipping gauge was used to calculate sprinkler delivery rates. The weather station was also used to identify rainfall events at the study site and provided local data for pan evaporation, temperature and relative humidity. An example of a live weather output provided by the weather station is given in Figure 4-1.

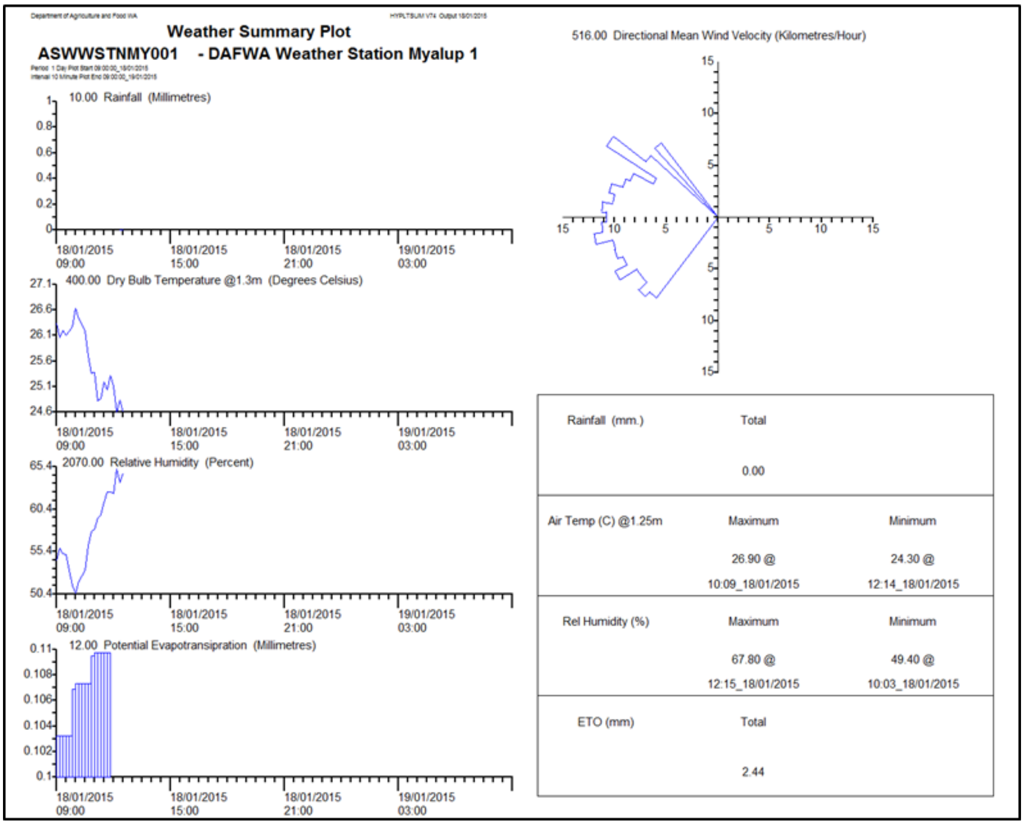

Figure 4-1: An example of the output provided by the Myalup automatic weather station (DAFWA 2015c).

4.2 Fieldwork observations

Three sets of data were examined for this investigation:

- Soil moisture (soil water content)
- Soil water salinity (electrical conductivity (EC) and total dissolved solids (TDS))
- The combined volume of sprinkler irrigation and rainwater application.

These were then considered in relation to parameters such as evaporation, temperature, humidity and rainfall provided by the weather station. Recording equipment was installed in vegetable crops over both the winter and summer growing seasons as outlined in Chapter 3.

Samples of soil were collected down the profile at representative intervals to ground truth the soil moisture recording equipment and determine the TDS in the free water available to the crop. The field visit schedule is given in Table 4-1.

Table 4-1: Field visit schedule for the duration of the research.

Date	Investigation	Activity
02/04/2011	P001	Site reconnaissance Collect soil samples Test W1,W2 and W3 water quality
09/04/2011	P001 P002 C001	Install monitoring equipment Soil sample collection Data retrieval Test W1,W2 and W3 water quality
15/04/2011	P001 P002 C001	Soil sample collection Data retrieval Test W1,W2 and W3 water quality
06/05/2011	P001 P002 C001	Retrieve equipment from P002 and C001 for maintenance Soil sample collection Data retrieval
28/05/2011	P001 P003 P004	Retrieve equipment from P001 Deploy crop and control equipment in P003 and P004 Soil sample collection
01/07/2011	P003 P004	Soil sample collection Data retrieval
20/08/2011	P003 P004	Retrieve monitoring equipment for maintenance Soil sample collection Test W1,W2 and W3 water quality
08/10/2011	P005 C002	Deploy equipment in P005 and C002 Soil sample collection
10/10/2011	P005 C002	Soil sample collection
05/11/2011	P005 C002	Soil sample collection Data retrieval Equipment maintenance Test W1,W2 and W3 water quality
04/12/2011	P005 C002	Retrieve monitoring equipment from P005 and C002 Retrieve data

	C003 O001	Collect soil samples Redeploy monitoring equipment in O001 and C003 Collect soil samples Test W1,W2 and W3 water quality
11/12/2011	C003 O001	Retrieve data Collect soil samples Collect laboratory water samples
20/12/2011	C003 O001	Retrieve data Collect soil samples
27/01/2011	C003 O001	Retrieve monitoring equipment from P005 and C002 Retrieve data Collect soil samples

The location of each investigation, as well as vegetable type and date are given in Figure 4-2 and detailed in Table 4-2.

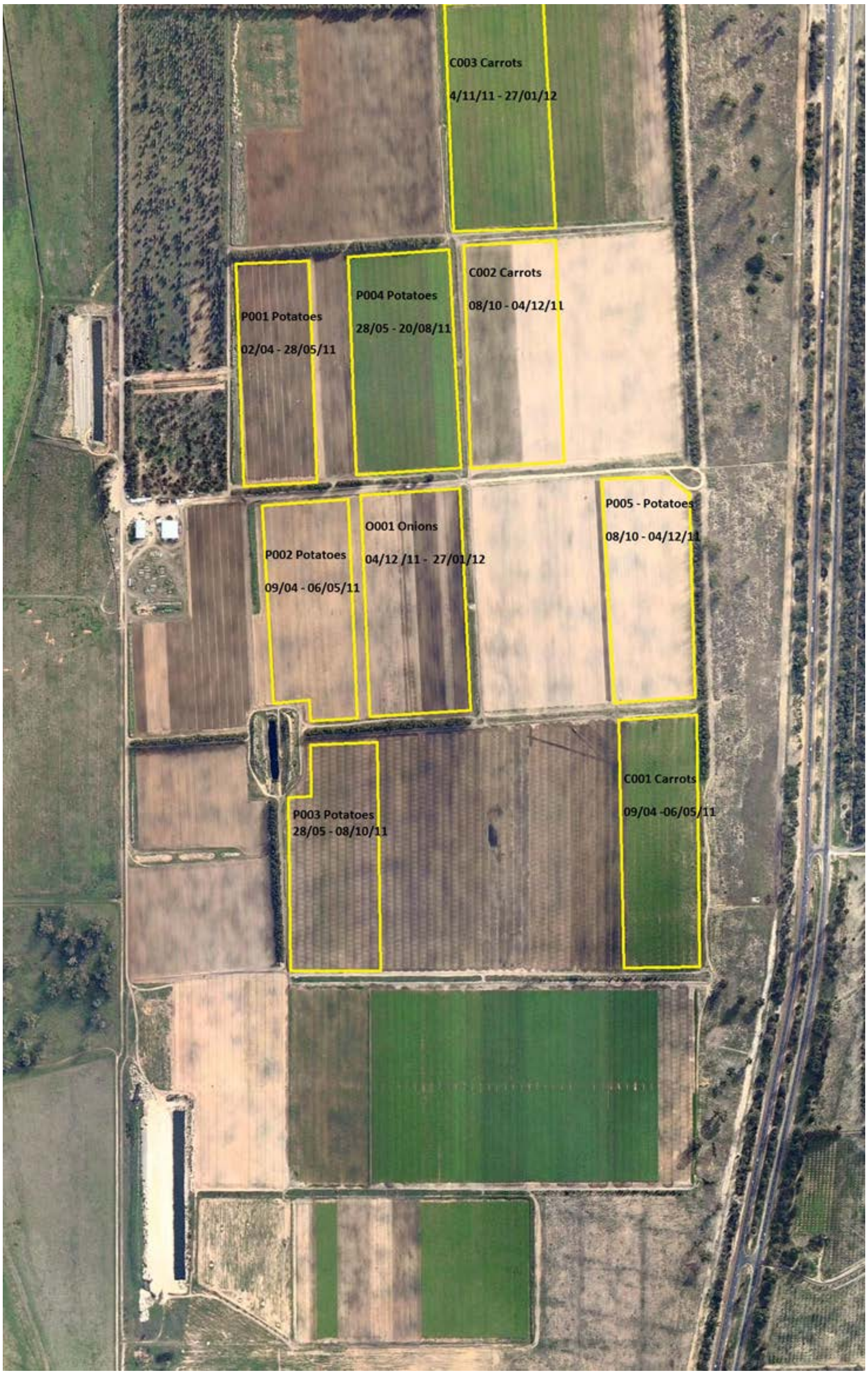

Figure 4-2: Location of investigations during the research period.

Table 4-2: Summary of investigations during the research period.

Investigation	Date		Crop type	GPS	
	Start	End		South	East
P001	02/04	28/05	Ruby Lou potato	33° 09′ 21.6″	115° 42′ 37.4″
P002	09/04	06/05	Potato	33° 09′ 34″	115° 42′ 36.2″
P003	28/05	08/10	Ruby Lou potato	33° 09′ 38.4″	115° 42′ 38.7″
P004	28/05	20/08	Potato	33° 09′ 11.2″	115° 42′ 44.2″
P005	08/10	04/12	Carisma™ potato	33° 09′ 22.2″	115° 43′ 01″
C001	09/04	06/05	Carrot	33° 09′ 37.5″	115° 42′ 55.2″
C002	08/10	04/12	Carrot	33° 09′ 21.6″	115° 42′56.9″
C003	04/12	27/01/2012	Carrot	33° 09′ 08″	115° 42′ 56″
O001	04/12	27/01/2012	Onion	33° 09′ 23.5″	115° 42′ 43″

As noted in Table 4-2, the data from two investigations were used for this research: P003, a winter potato crop and C003, a summer carrot crop.

4.3 Soil water content measurement

Three methods were used to measure soil water content: the thermogravimetric method, to obtain definitive results at a known time; measurements of soil water suspensions using electrical conductivity; and the dielectric method, to obtain a continuous indication in relation to irrigation, rainfall weather conditions and crop maturation. These are briefly outlined below.

4.3.1 Thermogravimetric method

Soil sample collection and analysis

Soil sample cores were collected down the soil profile within rows adjacent to the vegetables using a 120 cm long, 10 cm diameter polyvinyl chloride (PVC) tube with a serrated edge at intervals of (cm) 0–10, 10–20, 20–30, 30–40 and 40–50 - chosen to correspond with 80% of the depths recorded by the capacitance probes. Soil intervals are hereafter referred to as 10–¬, 20–, 30– and 50 cm and there is an offset in the measurements because the capacitance sensor effectively recorded at the base of each interval. While the sensor only measured the four intervals, the 30–40 cm interval was retained and analysed.

The coring tube easily penetrated the soil profile in the first three intervals to approximately 30 cm, thereafter clockwise rotation was applied using a 2 cm diameter steel tube, inserted through two 2.5 cm predrilled holes at the upper end of the tool in the same manner as that of a manual auger tool (Figure 4-3).

Upon extraction, soil samples within the core were removed at each 10 cm interval, split into halves and placed into sealed and labelled polythene bags. Samples were weighed on site and placed in a sealed plastic bucket for transport to Perth for soil moisture and salinity determination.

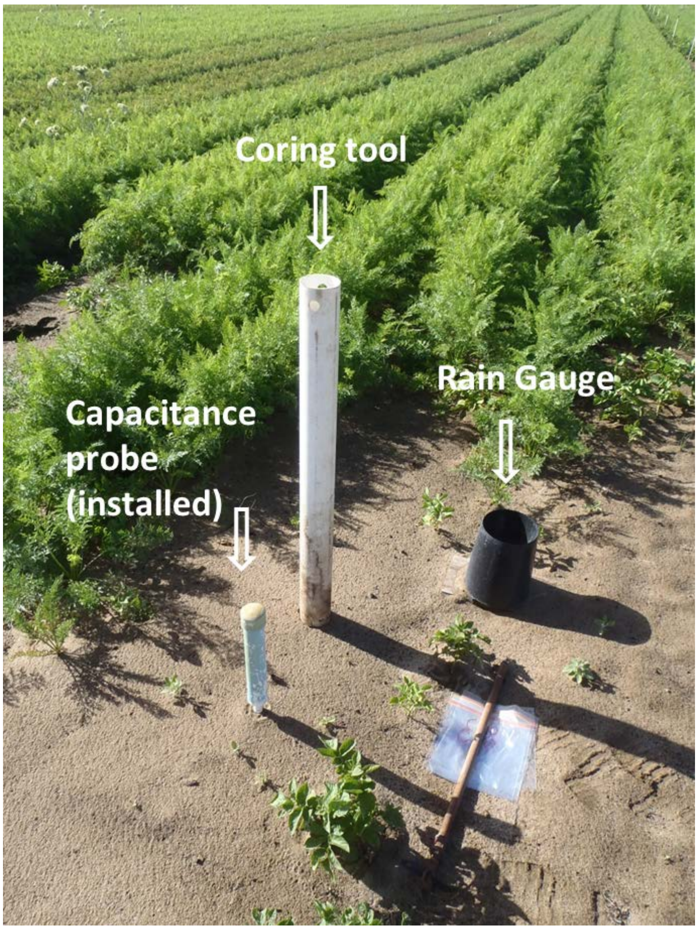

Figure 4-3: Coring tool shown *in situ* with the Odyssey capacitance probe and Odyssey tipping bucket rain gauge, sample bags and coring tube handle.

Gravimetric water content (θ_g) is the mass of water per mass of dry soil. It is measured by weighing the soil sample (m_{wet}), drying it to remove the water and reweighing the dry soil (m_{dry}) (Black 1965; Bilskie 2001). The following procedure described in Black (1965) and Smith and Mullins (2000) was followed:

- Weigh aluminium tin, and record its weight (tare).
- Place a soil sample in the tin and record the weight (wet soil + tare).
- Place the sample and tin in an oven at 105°C overnight to dry.
- Weigh the sample and record this weight as weight of (dry soil + tare).

The advantages of this method are that it ensures accurate measurement and is not dependent on salinity and soil types (Zazueta and Xin 1994). The following equation was then used to determine the soil water content:

$$\theta_g = \frac{m_{water}}{m_{soil}} = \frac{m_{wet} - m_{dry}}{m_{dry}}$$

The gravimetric water content (θg) was also used to calibrate values recorded by the Odyssey capacitance probes.

4.3.2 Soil water salinity

Soil water salinity was measured on duplicate samples via the electrical conductivity (EC) of a suspended soil solution. The sample was placed into a container and rinsed with a measured volume of distilled water at an approximate ratio of 1:5, taking into consideration soil water content and thoroughly mixed. The EC was then measured using a calibrated handheld meter (YSI EcoSense EC300) and converted to TDS.

Standardising soil salinity

The times at which the collection of soil samples took place during field visits varied throughout the day and in relation to irrigation and precipitation. Assuming salinity of soil moisture varies substantially in response to daily irrigation and precipitation, and evapotranspiration, it is necessary to transform recorded moisture values to a common water content to calculate salt accumulation to gain relative values and provide a comparison across each sample.

A standard value was calculated for recorded values at three moisture percentages realistically representing the observed range of soil moisture content. These were 4, 6 and 8%, The calculation required for this was to divide the recorded soil water percentage by the required standardised percentage (i.e. 4, 6 or 8) then multiply by the recorded or actual TDS value.

4.3.3 Dielectric method (multisensor capacitance probe)

The Odyssey Soil Moisture Recording System (Odyssey 2014) was used to continuously monitor *in situ* soil water content at 15-minute intervals. It comprised a multisensor capacitance probe connected to a battery-powered data logger. A PVC access tube housed the sensor rod which enabled the assembly to be removed for maintenance and data to be downloaded without disturbing the soil profile.

Equipment installation

A central position within the crop row (Figure 4-6) was chosen for the probe installation using the following procedure. A hollow steel tube of slightly smaller outside diameter to the sensor was rotated and driven vertically through the soil profile to approximately 50 cm at the location within the crop chosen for the sensor. The soil being captured as the steel tube passed through the profile.

The steel tube, along with the captured soil core, was then removed leaving a hole in which to install the sensor assembly ensuring minimal compaction of the soil surrounding the sensor which would otherwise result in distorted measurements. A PVC access tube was then pushed into the hole and tapped firmly into position. After activation of the data logger, the sensor assembly was then inserted into the PVC access tube and proceeded to record (Figure 4-4).

Communication was continuously maintained with the horticultural property manager, who provided notification of when removal of the monitoring equipment was required due to harvesting or in the event of a crop failure.

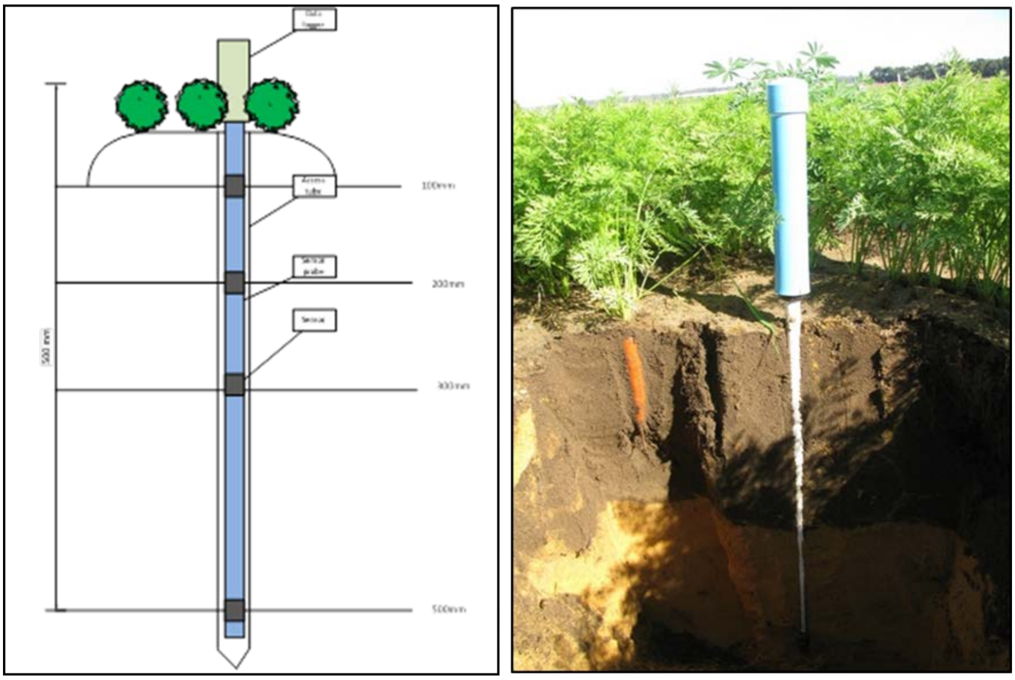

Figure 4-4: (Left) Cross-section of Odyssey capacitance probe illustrating components and (Right) its installation in a carrot crop demonstrating its relation to soil types and crop depth.

The capacitance technique measures the apparent dielectric constant of the soil surrounding the sensor, which reflects the water content of the soil-water-air mixture, to determine soil water content (Fares and Alva 2000). Sensor points along the probe measured soil water content every 15 minutes at four depths 10-, 20-, 30- and 50 cm and, for the purposes of the research described here, these sensor depths are reflective of the following soil intervals (cm): 0–10, 10–20, 20–30 and 40–50. The 10-, 20- and 30 cm intervals were representative of the root depth and the 50 cm interval represents the depth at which the soil water content (within undisturbed Cottesloe sand) indicates effective leaching past the root zone.

Soil moisture at each interval was time stamped and stored for subsequent download using the Odyssey software and exported to either Microsoft Excel™ or Stata™. An example of the Odyssey software graphical output illustrating soil moisture at each of the predetermined intervals is given in Figure 4-5.

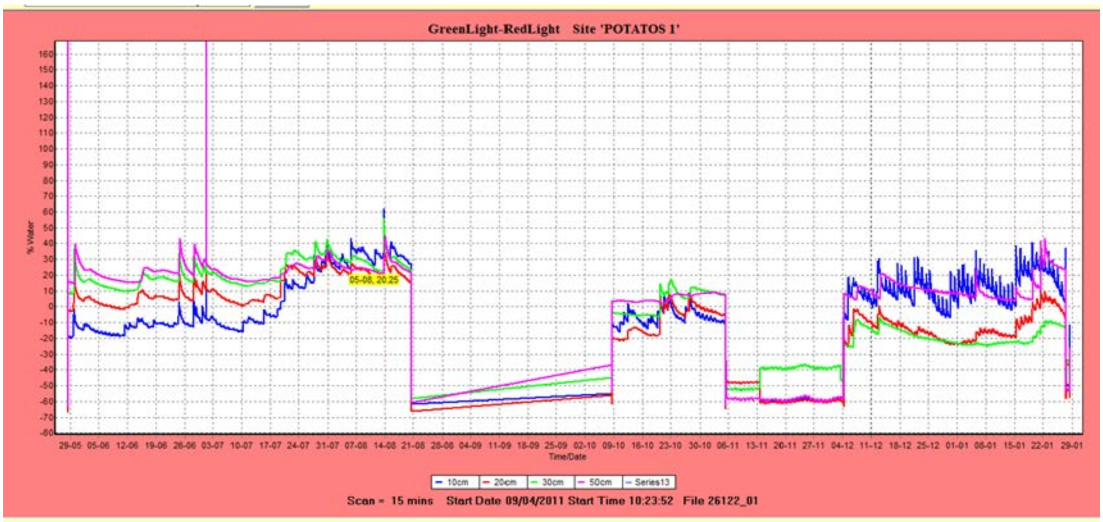

Figure 4-5: An example of the readout from the Odyssey software.

Potential limitations associated the soil moisture probes

With the exception of equipment maintenance and relocation, soil moisture data was recorded continuously over the 11-month investigation period. Relocation of the instruments across the horticultural property resulted in calibration errors occasionally resulting in data loss

The latter stages of fieldwork indicated that settlement of the tilled, humic soil, combined with the compaction of the growing crop, potentially adversely affected sensor readings. It was also discovered that vegetables adjacent to the sensors contributed to soil moisture readings. To combat this, soil samples were collected (as described above) on installation of the probes into a new trial and analysed gravimetrically to provide a control value for the soil moisture probe. Instrument data were subsequently transformed in an attempt to ensure their accuracy. However there were some flaws generating erroneous negative values that caused issues. In addition, low sample numbers for each short-duration investigation meant that the recalibrated values did not truly reflect the correct moisture reading when reverted. This was considered to be due to the changing structure of the soil and associated soil moisture content as the crop matured.

4.4 Sprinkler water volume and rainfall

Previous observations indicated that site infiltration was 100%, even in very heavy rain periods and runoff has never been observed. Thus tipping bucket rain gauges were installed in crop locations corresponding to the capacitance probes to measure the volume of irrigation water applied to the crop and rainfall events at ground level.

An estimation was also made of sprinkler water evaporation between the sprinkler head and the ground by measuring any changes in TDS. Collection dishes were used to obtain ground level samples and TDS measured using a handheld conductivity meter.

4.4.1 Tipping bucket rain gauge and data logger

Each collection bucket was 16 cm in diameter by 24 cm high and was calibrated by pouring a measured volume of water through the bucket and converting it to precipitation in mm. An Odyssey data logger was connected to a Davis Instruments gauge and fitted within each bucket (Odyssey 2014). Figure 4-6 illustrates the layout adopted for the equipment in the investigations.

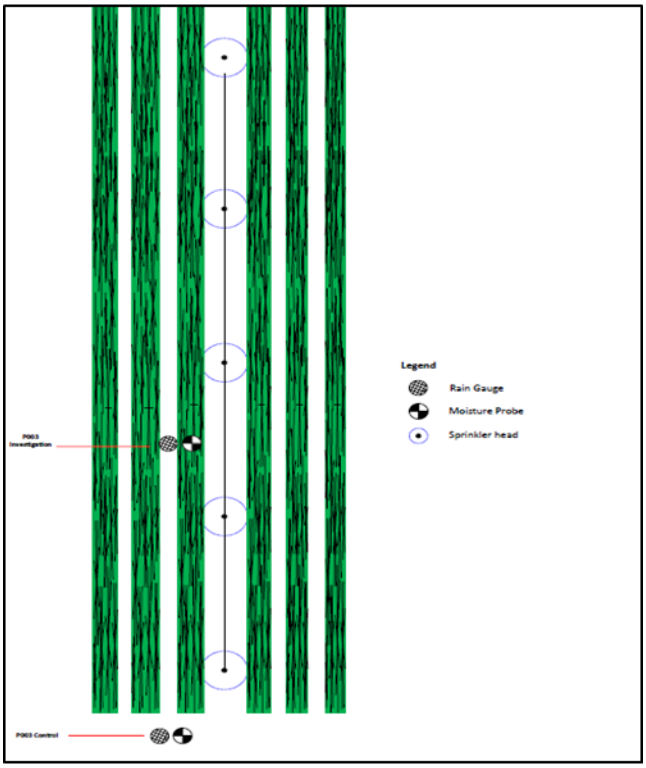

Figure 4-6: Plan view of instrument placement within the crop.

4.4.2 Investigation control

Control data were collected on a selection of the investigations and involved the installation of a soil moisture probe and rain gauge under the same environmental conditions outside of the crop-growing area. Control soil samples were also collected and analysed using methods described above.

4.5 Groundwater quality

TDS and nitrogen profiles from W1, W2, and W3 (Figure 3-1) which supply irrigation water to the vegetable crops, as well monitoring bore MB2, were recorded. Routine laboratory analyses of water samples from the sources were conducted by the horticultural station's management staff and provided to support this research. In addition to these analyses, TDS readings were also collected from the same sites using handheld meter (YSI EcoSense EC300) as described in Section 4.3.2.

CHAPTER 5. RESULTS

This chapter describes the results obtained from investigating if seasonal rainfall is sufficient to effectively rinse the soil profile of salts and replenish the irrigation source water. The following data for the P003 winter Ruby Lou potato crop and the C003 summer carrot crop are presented: rainfall and irrigation application; soil water content; and crop salinity. This is followed by a description of the groundwater quality data, including TDS and nitrogen concentrations.

5.1 P003 winter Ruby Lou potato crop

5.1.1 Crop precipitation

Weather data

Mean pan evaporation data recorded by the Myalup weather station for the winter investigation was 2.25% (Figure 5-1). Five rainfall events of more than 30 mm occurred, a number before the crops were planted and total rainfall over the 85 day investigation period was 451 mm.

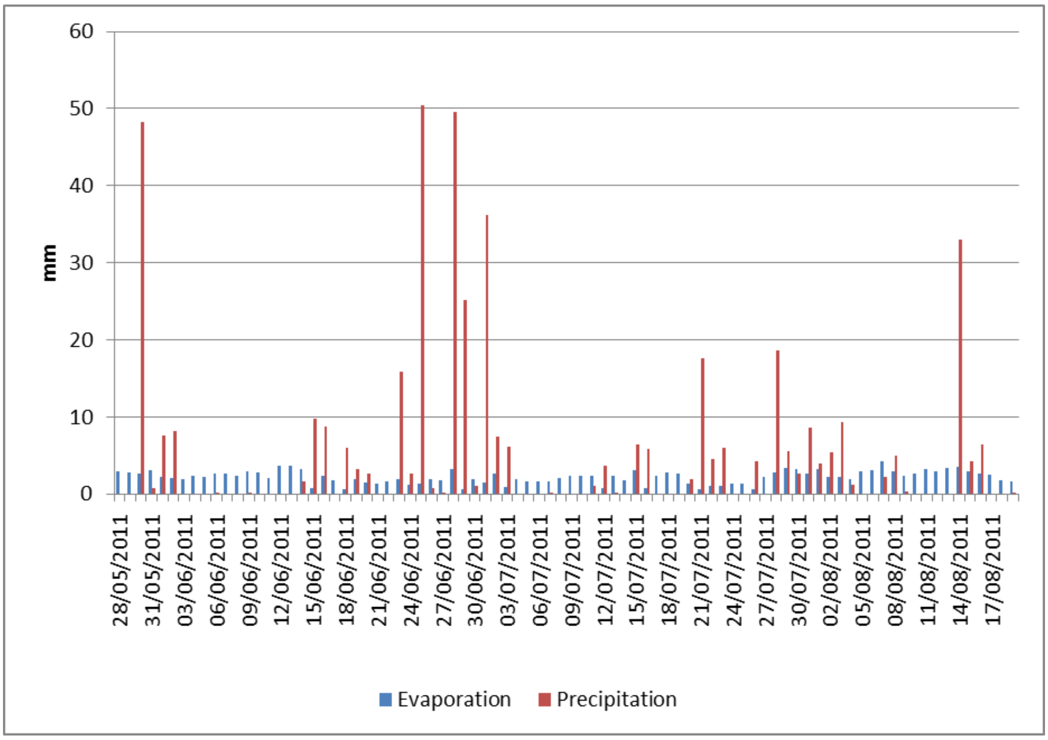

Figure 5-1: Precipitation and evaporation data recorded at the Myalup weather station illustrates the low evaporation rates experienced during investigation P003.

Rain gauge data

Total crop precipitation/irrigation was 597 mm for the investigation period (Figure 5-2) while the total irrigation water received by the crop was 146 mm.

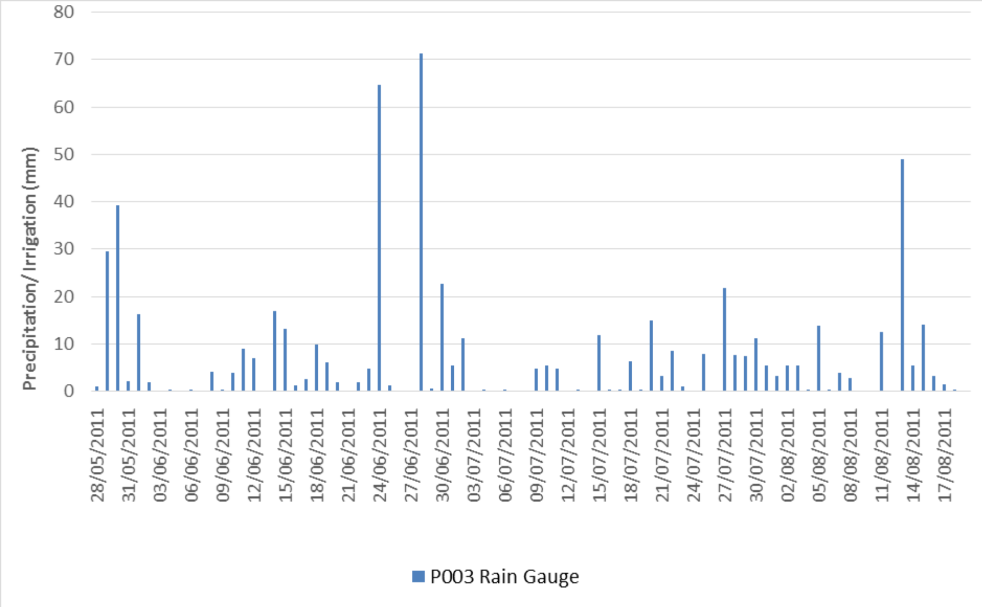

Figure 5-2: P003 crop rain gauge results highlight three heavy rainfall events which occurred on 25/06/11, 28/06/11 and 13/08/11 respectively.

In comparison, the control rain gauge installed just outside the crop collected a total precipitation/irrigation value of 564 mm (Figure 5-3).

Given these results, total applied water to the crop for the investigation was calculated at 146 mm while the total applied water at the control was 113 mm. The increased volume recorded by the crop rain gauge in the early stages of the investigation can be attributed to exposure to increased volumes of applied water. This was a result of the rain gauge placement within the crop and within the area covered by the overhead sprinkler array. The control rain gauge was placed at the outside edge of the irrigated area and thus only exposed to the water applied by one sprinkler head.

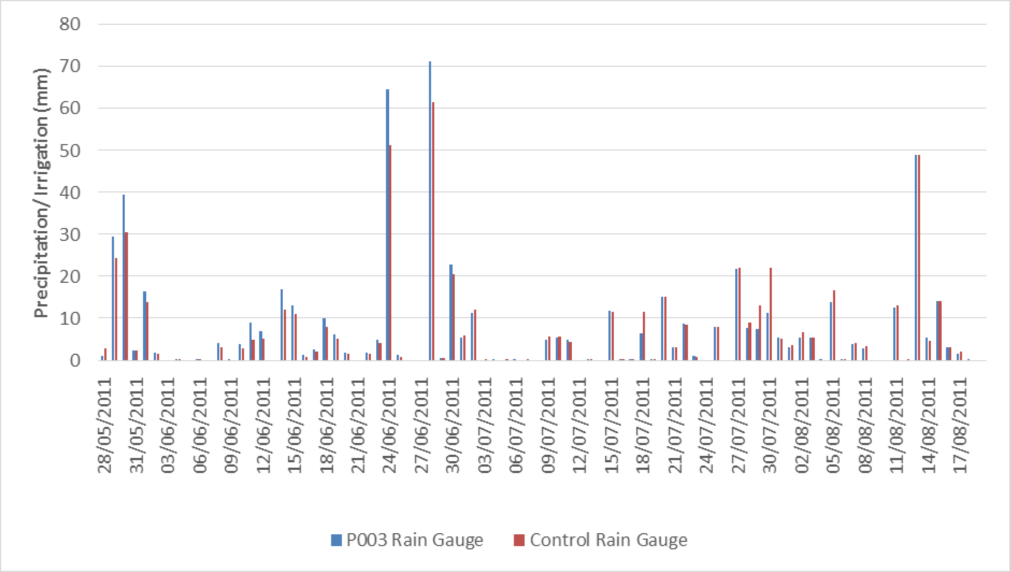

Figure 5-3: P003 crop and control rain gauge results illustrate minor differences observed between gauges; in particular, toward the end of the investigation as the crop reaches maturity.

In the early stages of crop development, the rain gauges were also found to be subject to mild silting within the instrument's funnel due to sand being splashed by heavy rainfall. High wind, absence of adequate windbreaks, minimal ground cover and foliage appeared to cause a moderate amount of soil to be displaced, which was evident by soil on the side of the rain gauges (Figure 5-4).

Figure 5-4: The effect of high wind and rain on the soil during the investigation on 01/07/2011.

It was observed that the volume of water recorded and the time at which it passed through the funnel may not have reflected the actual time of precipitation and/or irrigation. This affected observations in both the crop and control rain gauges at certain times. However, it was considered that the discrepancy did not materially affect the interpretation of results.

During the latter stages of crop maturation, the rain gauge funnel was occasionally found to be shaded by the plant leaves. This had the effect of either deflecting and/or channelling rainfall and/or sprinkler application, depending on the how the foliage obstructed the instrument (Figure 5-5).

Figure 5-5: The rain gauges situated under foliage within a potato crop (left) and in an onion crop (right).

This observation is evident in Figure 5-3 indicating that toward the end of the crop, the crop rain gauge was found to receive less precipitation and/or irrigation than that of the control.

Wind speed and direction were also found to affect the uniformity of irrigated water dispersion. Strong winds, prevalent from the east during the morning watering period in summer months, often carried water across the crop resulting in uneven application. It was considered however that the volume of water received at the soil surface corresponded adequately with the soil water content recorded by the associated capacitance probe.

Precipitation and irrigation water

A comparison of results from the in situ rain gauge are plotted with Myalup weather station rainfall data in Figure 5-6. The absence of weather station rainfall data and the presence of in situ data are indicative of an irrigation application. This was verified by records maintained by the horticultural managers.

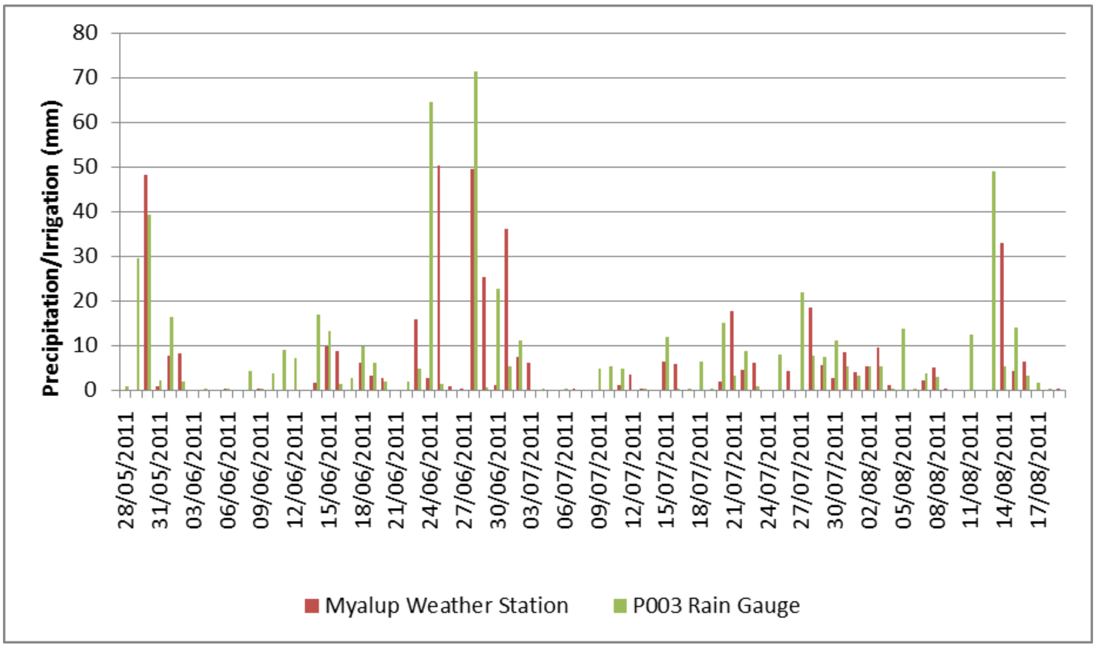

Figure 5-6: A comparison of rain data from the Myalup weather station and in situ rain gauge identifying days in which rain fell, days in which irrigation water was applied, and days of both irrigation and rain.

As noted earlier, irrigation is applied during the winter growing period for initial pre-irrigation practices, fertigation and frost control. In comparison to the summer, very little irrigation is required during the winter growing period. Of the 597 mm total crop precipitation/irrigation recorded, rainfall comprised approximately 75 per cent (451 mm) and irrigation 25 per cent (146 mm).

The Myalup weather station records data from 09:00 to 09:00 on the following day. The Odyssey rain gauges recorded data between 00:00 and 00:00 on the following day. Figure 5-6 shows how a number of showers may comprise a daily total. It also shows that the similarity of readings is good, other than for the high rainfall events between 24/06/11 and 01/07/11.

Rainfall intensity and duration

Documentation of rainfall percolation through the soil profile of crops to determine if, when, and how rinsing of accumulated salt occurs was essential to the investigation and three high rainfall winter events of short duration were investigated. A summary of the winter rainfall events that were analysed is presented in Table 5-1 and graphically in Figure 5-7 to Figure 5-9.

Table 5-1: Summary of P003 rainfall events.

Date	Event	Crop precipitation
24/06/2011	A	64 mm
28/06/2011	B	71 mm
13/08/2011	C	49 mm

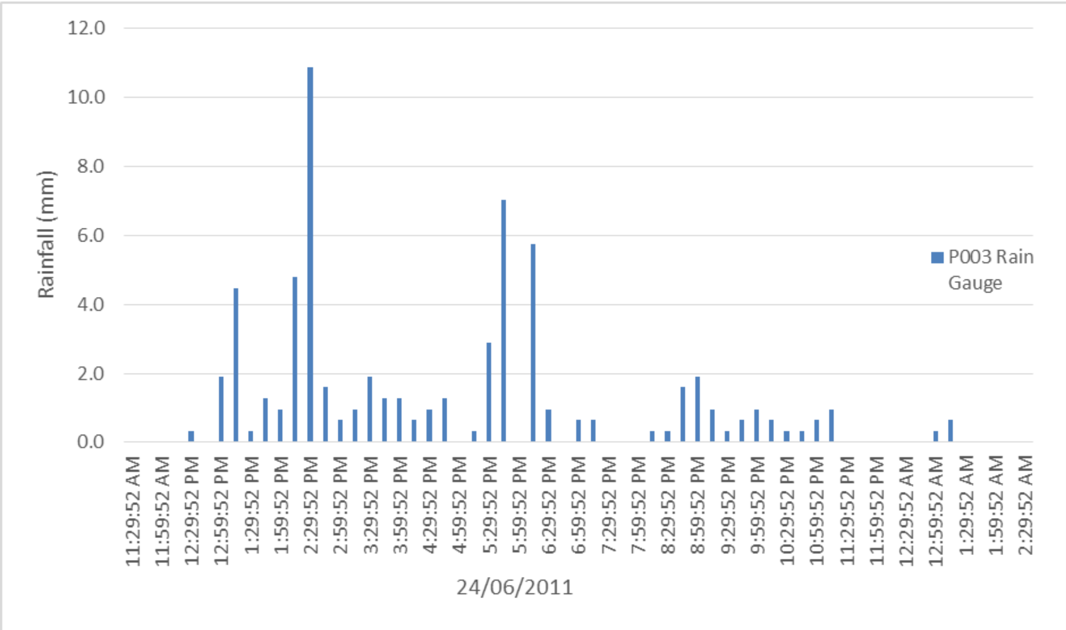

Figure 5-7: P003 rainfall Event A occurring 24/06/2011 with rainfall intensity shown in 15 minute intervals.

Results for Event A indicate that crop precipitation was 64 mm over 12 hours, with the highest intensity (11 mm) falling over a 15-minute period. Crop precipitation was 64 mm, the Myalup station recorded 50.4 mm and the control rain gauge indicated 51.3 mm. As crop precipitation was 12.7 mm greater than the control and 13.6 mm greater than the weather station record, it is probable that additional water was applied to the crop by the horticultural managers during this event.

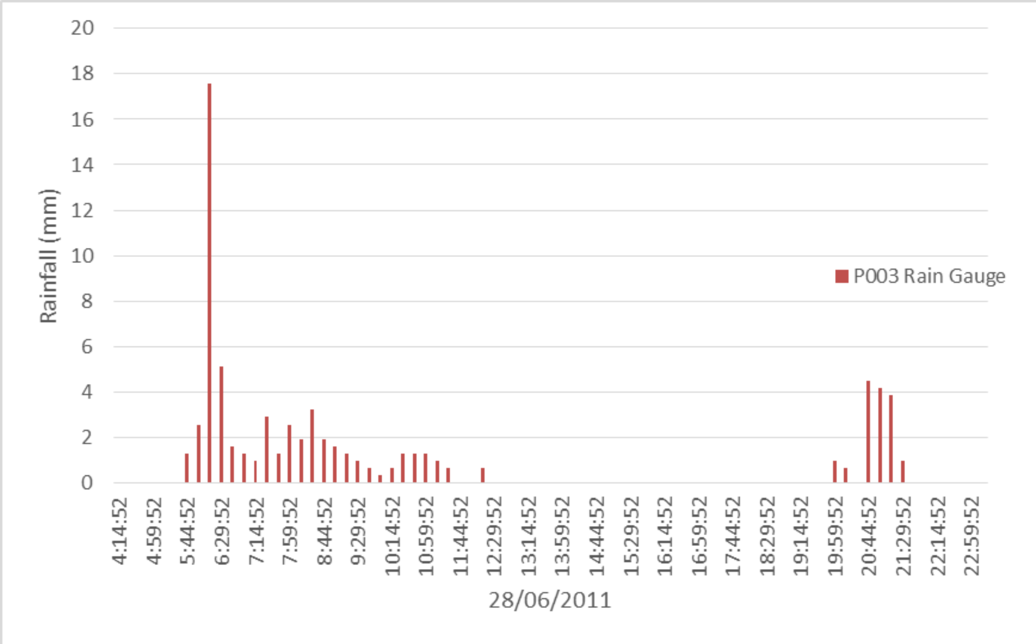

Figure 5-8: P003 rainfall Event B occurring on 28/06/2011 with rainfall intensity shown in 15 minute intervals.

Event B crop precipitation was 71 mm over about six hours although an additional fall was captured and recorded as the same event. Approximately 18 mm fell in one 15-minute interval. Event B was the highest recorded daily rainfall total for the investigation period. The Myalup weather station recorded 49.6 mm (however, it recorded 25.2 mm the following day) and the control rain gauge indicated 61.6 mm. Event C had 49 mm precipitation over five hours with nearly 30 mm recorded in one hour (Figure 5-9).

In general, results from all three events indicate that the control rain gauge recorded 24 per cent less applied water than that of the crop rain gauge.

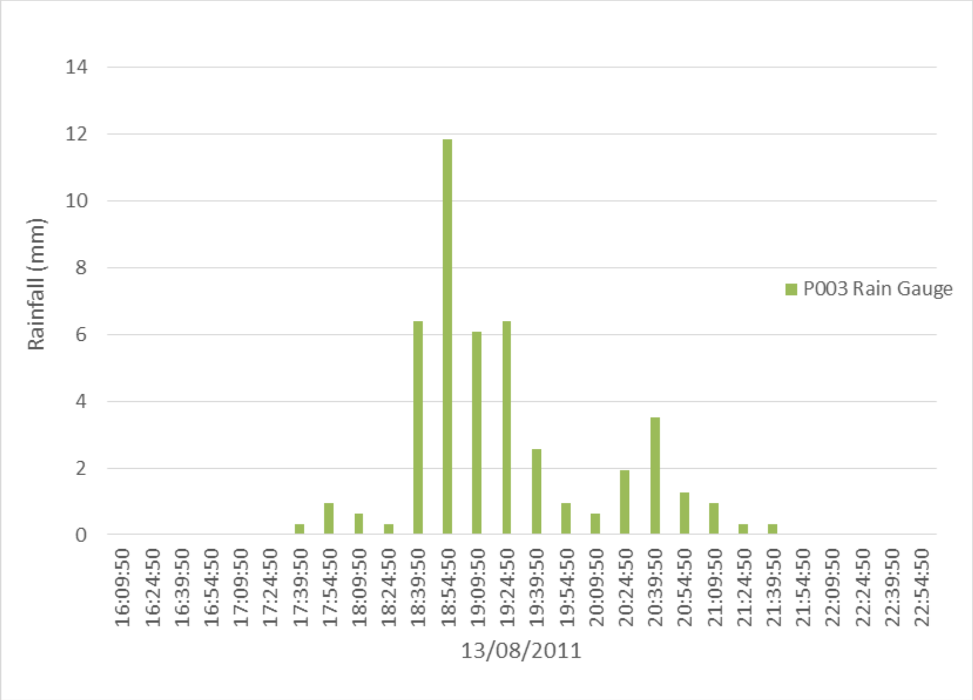

Figure 5-9: P003 rainfall Event C occurring 13/08/2011 with rainfall intensity shown in 15 minute intervals.

5.1.2 Soil water content

Gravimetric soil moisture

Gravimetric soil water content measured during the P003 investigation demonstrated that the soil retained high moisture through the soil profile with the exception of the 50 cm interval on 20/08/2011 (Figure 5-10).

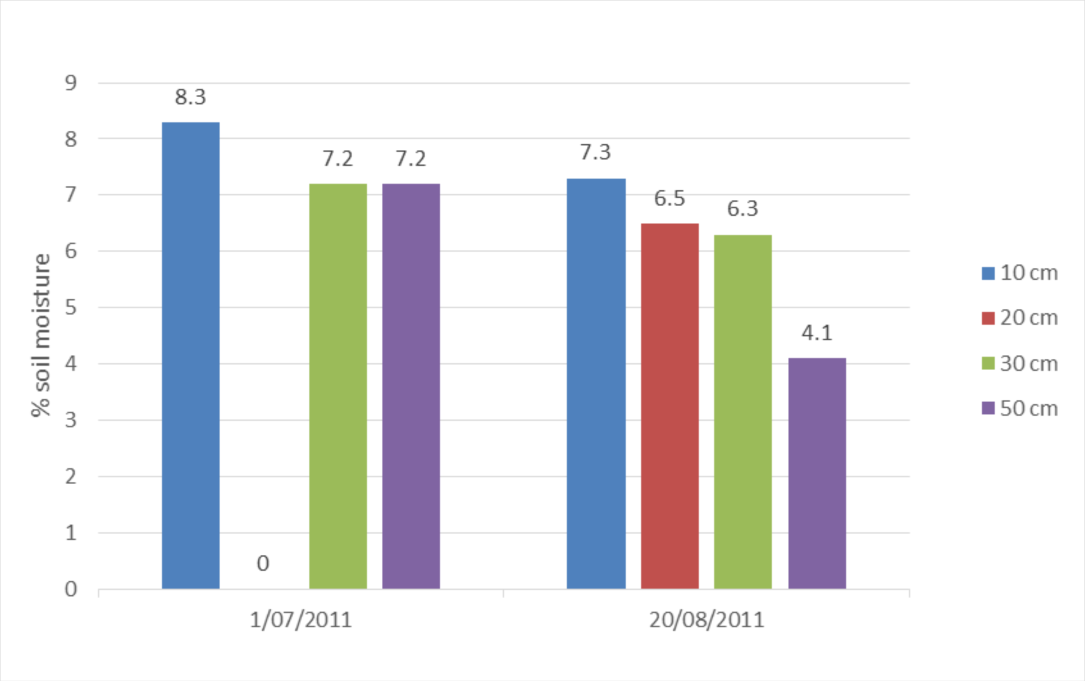

Figure 5-10: Gravimetric soil water content is presented for two occasions through the investigation period. No data was recorded at the 20 cm interval on 01/07/2011.

Soil samples were taken at 08:00 on the 01/07/2011 and 14:00 on 20/08/2011.

Probe soil moisture

In the results presented here, it is important to note that the traces are not given in order down the profile, nor do they reflect true quantitative results. Interpretation was facilitated by taking soil samples and directly analysing them for both moisture content and TDS of the soil moisture. Changes in soil compaction and growth of vegetables close to the probe sensors led to changes in sensitivity that would have required continual recalibration. It was concluded that precise quantitative data was not required to answer the research question in regard to sustainability. To address this, the qualitative results down the soil profile in response to potential rinsing events are required and qualitative raw data was used from the P003 and C003 investigations.

Uncalibrated soil moisture values for P003 are given in Figure 5-11 during which time the crop was maturing and the soil compacting. Uncalibrated soil moisture values for the control moisture probe are given in Figure 5-12. Crop precipitation volume and intensity at 15-minute intervals is also given or comparison in Figure 5-11 and Figure 5-12, along with Rain events A, B and C.

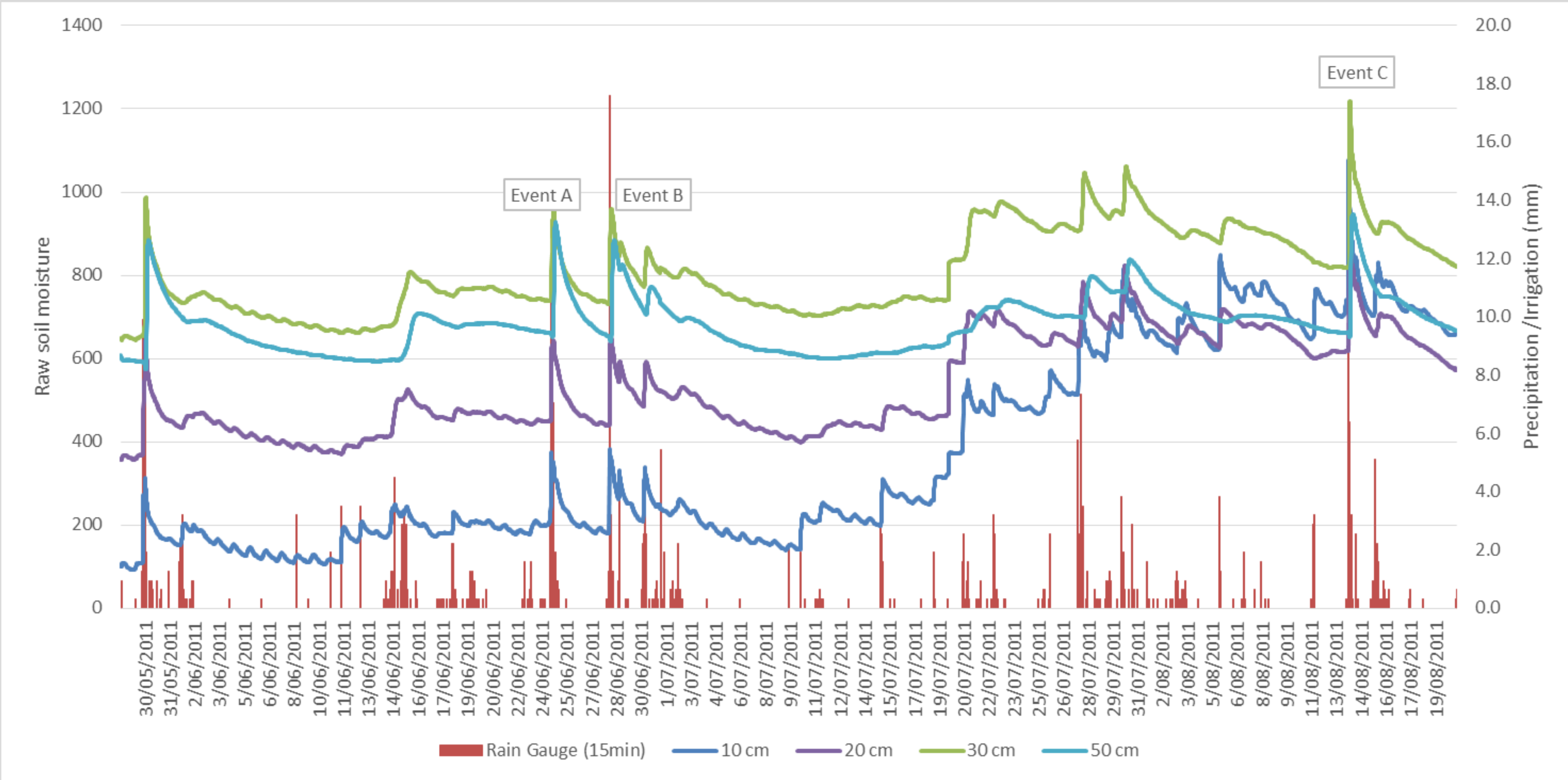

Figure 5-11: P003 uncalibrated soil moisture illustrating effective infiltration through the 10-, 20-, 30- and 50 cm intervals down the profile in response to daily water. Note that the 10 cm and 20 cm sensors read below the 50 cm sensor which is an instrument aberration in read-out.

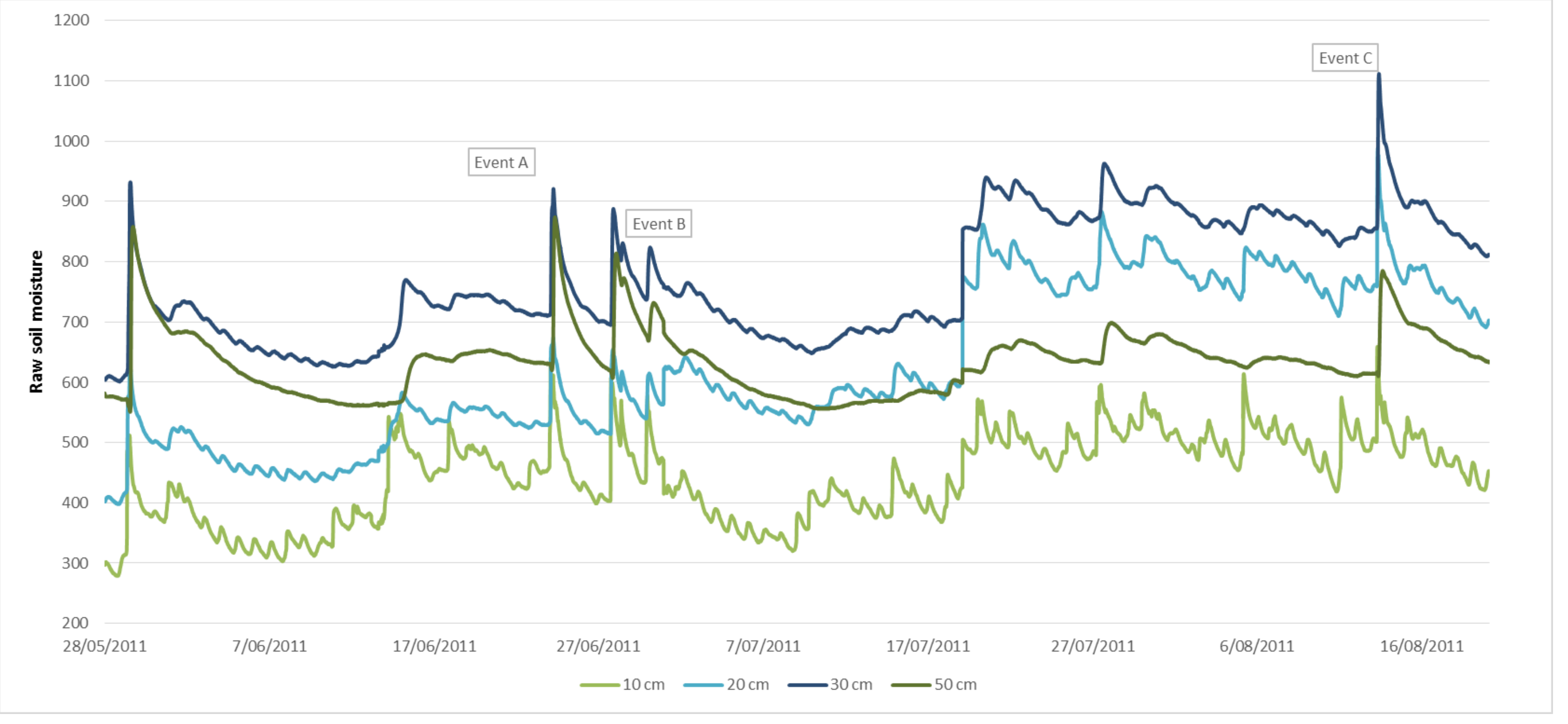

Figure 5-12: Uncalibrated 'control' soil moisture output illustrates effective infiltration through the 10-, 20-, 30- and 50 cm intervals down the profile in response to daily water.

There was an escalation in soil moisture approximately seven weeks into the investigation (Figure 5-11) from 10/07/2011 at 10 cm and 20 cm, but little response at 30 and 50 cm. There is a marked response at all levels after 18/07/2011. Soil moisture recorded at the control site (Figure 5-14), just outside of the cropped area, also showed escalation at the 20 cm and 30 cm intervals on 18/07/2011. No rainfall was recorded on 18/07/2011. However, the rain gauge did record 6.4 mm, likely a result of applied water or fertigation from the irrigators.

The sharp increase and decrease of the 50 cm soil moisture curve (Figure 5-13) indicates that soil saturation limits had been reached. The four clear responses observed in the 50 cm moisture curve include Events A, B and C.

Response to rainfall events

Figure 5-13 through to Figure 5-15 show rainfall data overlayed with soil moisture in response to Events A, B and C respectively. The qualitative data demonstrate the rate of infiltration and indicate approximate times at which percolation through the soil profile past the root zone occurred, thus rinsing it.

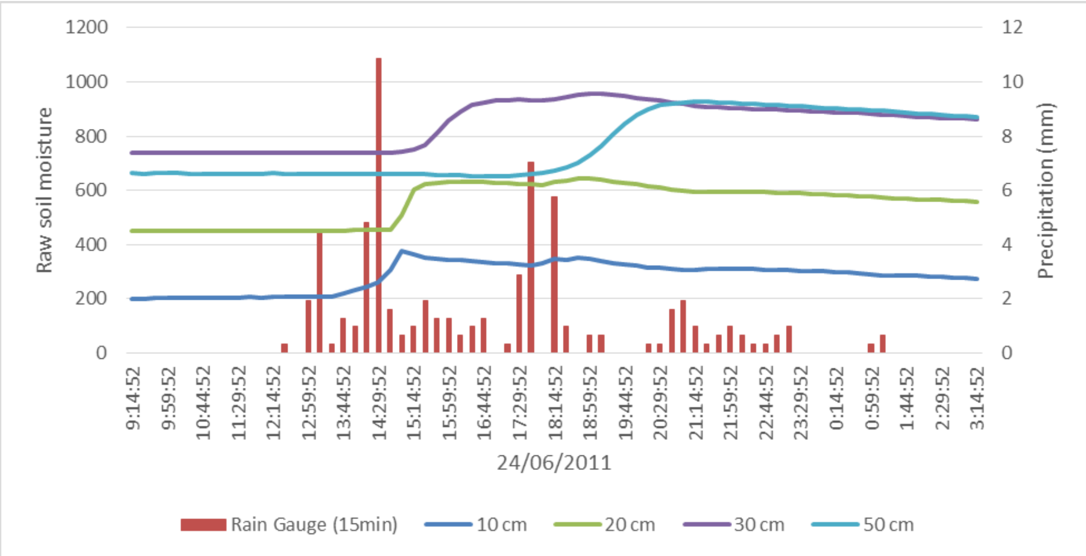

Figure 5-13: P003 soil moisture increases are shown at each interval down the soil profile in response to rainfall from Event A.

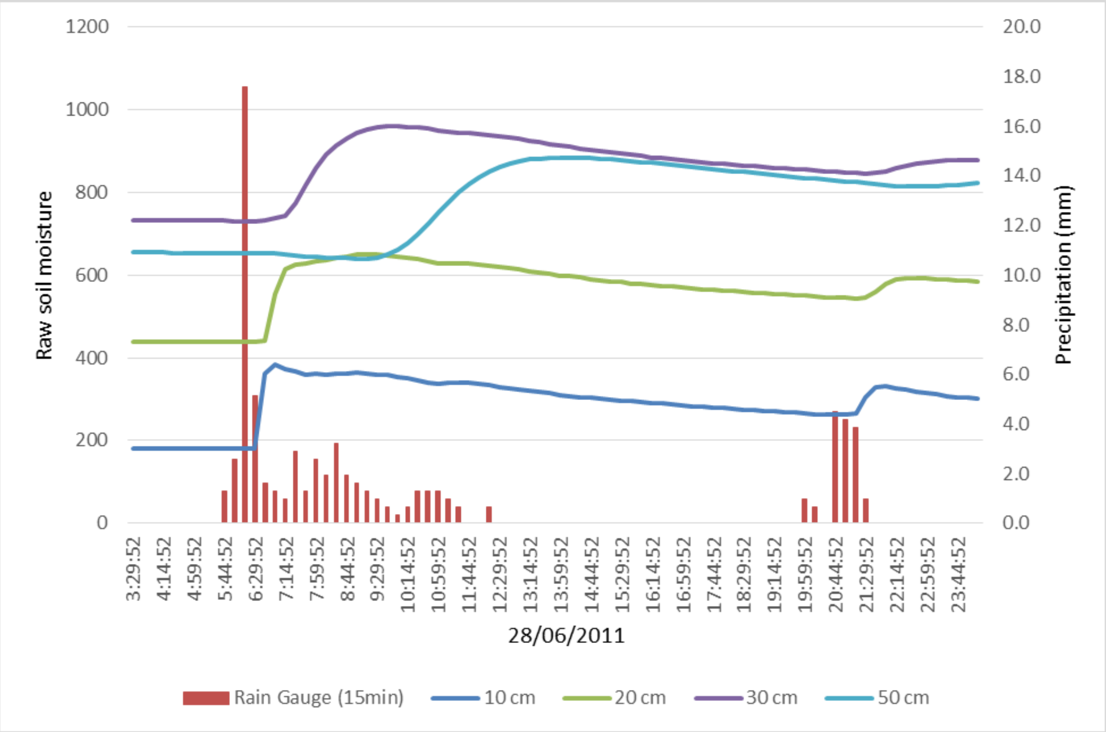

Figure 5-14: P003 soil moisture increases are shown at each interval down the soil profile in response to rainfall from Event B.

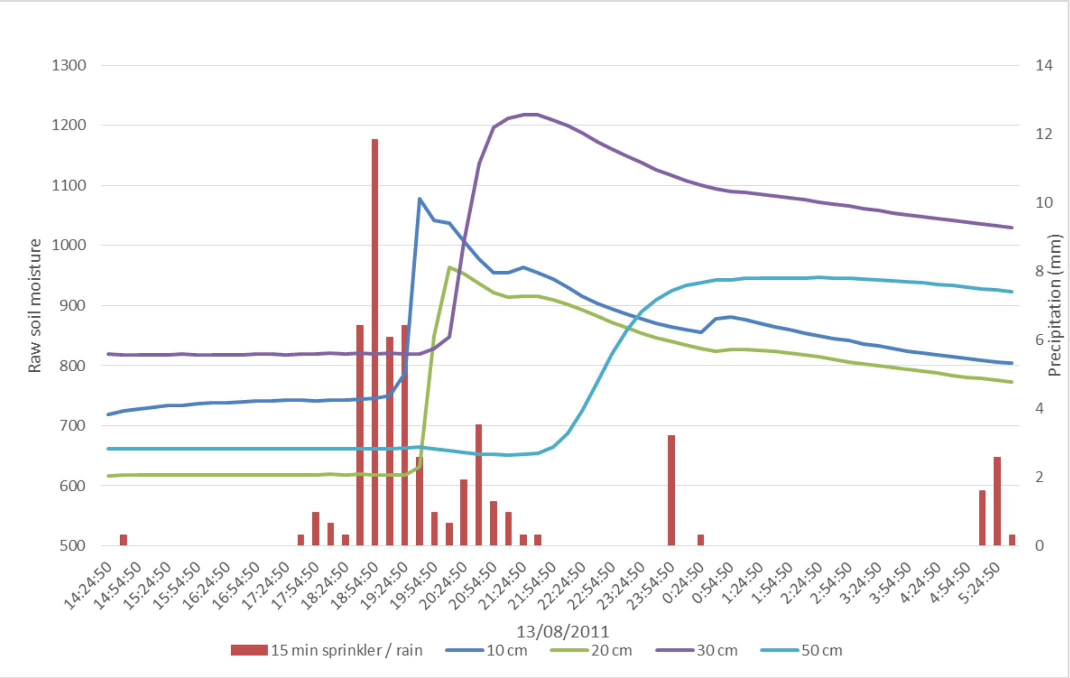

Figure 5-15: P003 soil moisture increases are shown at each interval down the soil profile in response to rainfall from Event C.

While the time taken for water to percolate from the surface to the 10 cm receptor is cannot be determined, the time taken between the other receptors is evident in the data. Based on the time taken to travel from the 10 cm interval to the 20 cm interval, it would appear to be 15–20 minutes. In general terms, the time taken for peak saturation to travel the 40 cm between the 10 cm and 50 cm sensors can be calculated to be from 1.5 to 3.5 hours.

Approximate response times for Events A, B and C to percolate through components of the soil profile are given in Table 5-2 excluding the time taken for water to move from the surface to the 10 cm interval.

Table 5-2: Moisture response times for rainfall Events A, B and C.

Interval (cm)	Time moisture detected (approx.)			Response from previous interval (mins)		
	A	**B**	**C**	**A**	**B**	**C**
10	13:30	06:30	19:10	×	×	×
20	14:45	06:45	19:25	15	15	15
30	15:00	07:00	19:55	15	15	30
50	16:00	09:45	21:40	60	165	105

Response times observed between the 10-, 20- and 30 cm intervals in general are similar, with the exception of Event C.

5.1.3 Soil salinity

Low TDS values generally occurred over the investigation period (Table 5-3). Results from samples taken on 01/07/2011 were preceded by rainfall events A and B. While salinities from 20/08/2011 all show an increase in TDS levels across all intervals. The 20 cm interval could not be compared to a previous salinity measure.

During the course of soil sampling, the results for the 20 cm profile were lost and are therefore presented accordingly as ‘no data’ (ND).

Table 5-3: Summary of salinity results for P003.

Date	Interval	Gravimetric moisture (%)	EC	TDS (ppm)
01/07/2011	10	8.3	587	376
	20	ND	ND	ND
	30	7.2	819	524

	50	7.2	1255	803
20/08/2011	10	7.3	4238	2712
	20	6.5	1843	1179
	30	6.3	1291	826
	50	4.1	3301	2113

ND = no data

Standardised soil moisture

Standard values were calculated at 4, 6 and 8% as they realistically reflect the range of soil moisture observed during the winter growing period and Figure 5-16 and Figure 5-17 give TDS at these values against the observed soil moisture for the two sampling events respectively. For the first sampling event, TDS increased with depth and appeared to be the effect of salts rinsing through the soil profile to reach the 50 cm interval. Similarly, on 20/08/2011, there was an increase of TDS at the 50 cm interval; however, the greatest TDS concentration was observed at the surface interval.

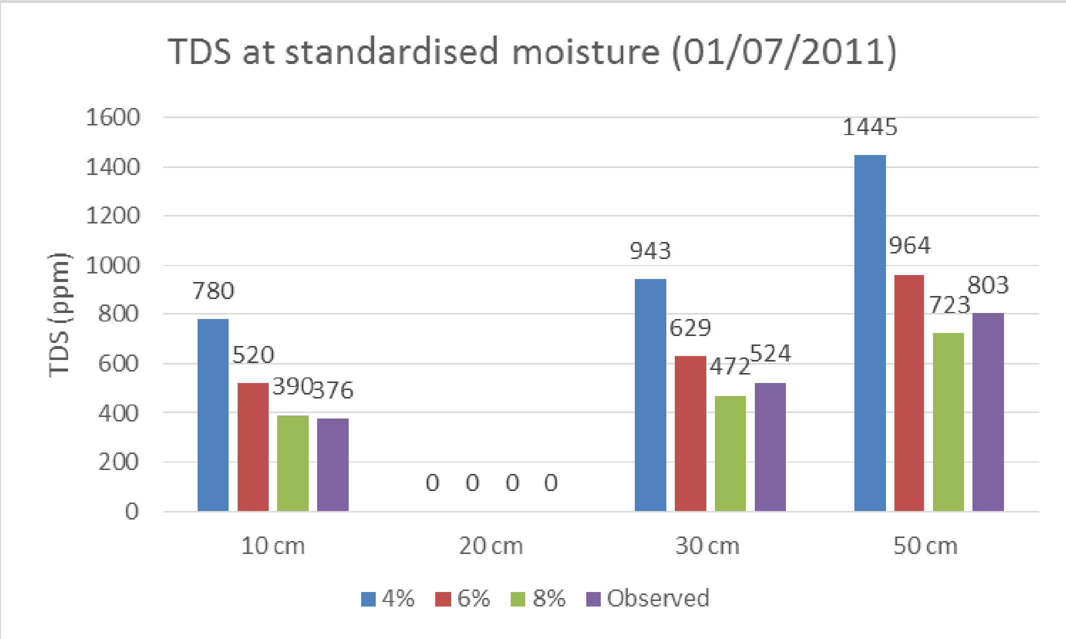

Figure 5-16: TDS at standardised and observed percentage of soil moisture on 01/07/2011.

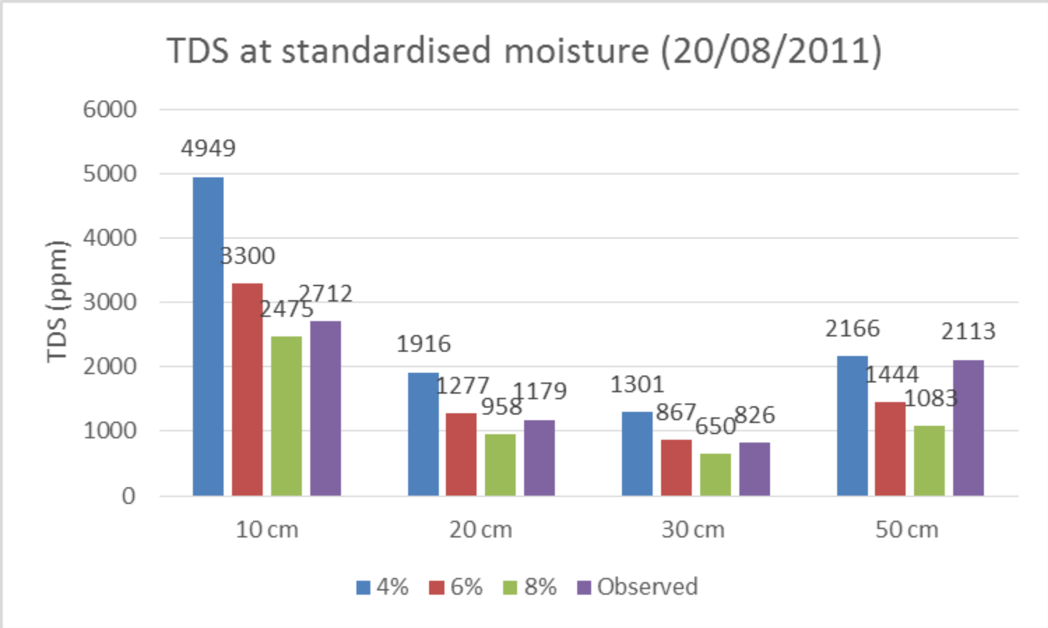

Figure 5-17: TDS at standardised and observed percentage of soil moisture on 20/08/2011.

While there were a number of rainfall events before the investigation, the total rainfall recorded at Myalup from its start (28/05/2011) to the first sample collection on 01/07/2011 was 242.8 mm. Total crop precipitation/irrigation was 334.4 mm and total applied water 91.6 mm, the latter having a TDS of 900 ppm. Using Brouwer and colleagues (1985) estimation, total salts applied to the crop during the investigation can be calculated as follows:

- 91.6 L of applied water per m^2 of crop = 916,000 litres per hectare
- 0.9 g/L × 91.6 L = 82 g of salt per m^2 = 0.82 tonnes of salt per hectare.

Total applied water recorded for the investigation was 146 mm and expected salts in the crop without rain or rinsing can be calculated as:

- 0.9 g/L × 146 = 1.31 g of salt per m^2 = 1.3 tonnes of salt per hectare.

Salinity and yield

Using the soil salinity yield threshold given for potatoes by PIRSA (2007, Table 5-4), soil salinities were below the threshold value at all observed levels, with the exception of the 10 cm interval on 20/08/2011 (Figure 5-18 and Figure 5-19).

Table 5-4: Potato yield threshold values (PIRSA 2007).

Yield	100% (EC/TDS)	75% (EC/TDS)	50% (EC/TDS)
Potato	3,400/2,176	7,600/4,864	11,800/7,552

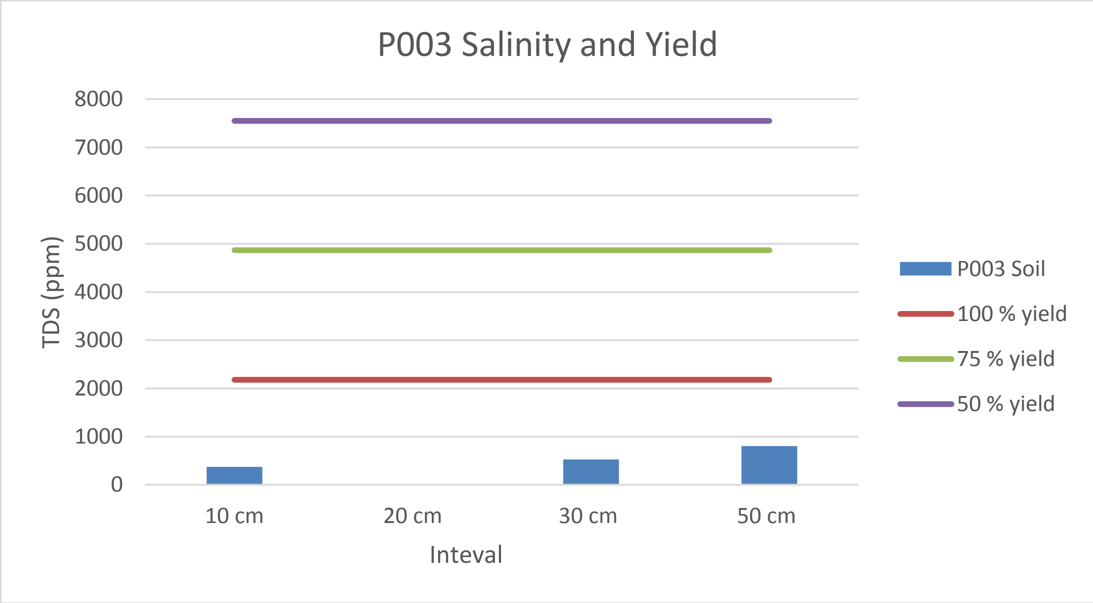

Figure 5-18: Soil TDS observed on 01/07/2011 show that they do not exceed recommended yield threshold values.

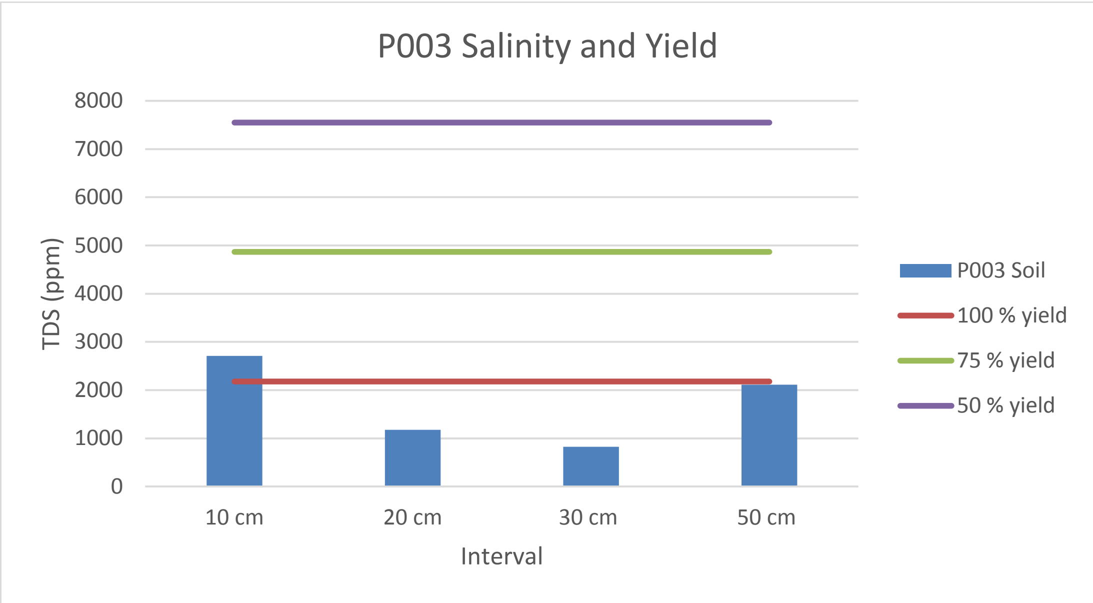

Figure 5-19: Soil TDS observed on 20/08/2011 show only a minor exceedance of the recommended yield threshold values.

Crop soil salinity was shown to be below the recommended 100 per cent yield threshold value at all observed levels, with the exception of the 10 cm interval on 20/08/2011.

5.2 C003 summer carrot crop

5.2.1 Crop precipitation

Weather data

Pan evaporation and rainfall were recorded by the adjacent Myalup weather station (Figure 5-20) and it is evident that high evaporation occurred over summer months compared to winter (7.75% vs 2.25% respectively). While two rainfall events greater than 20 mm were recorded by the station, the crop rain gauge only recorded one event at greater than this value.

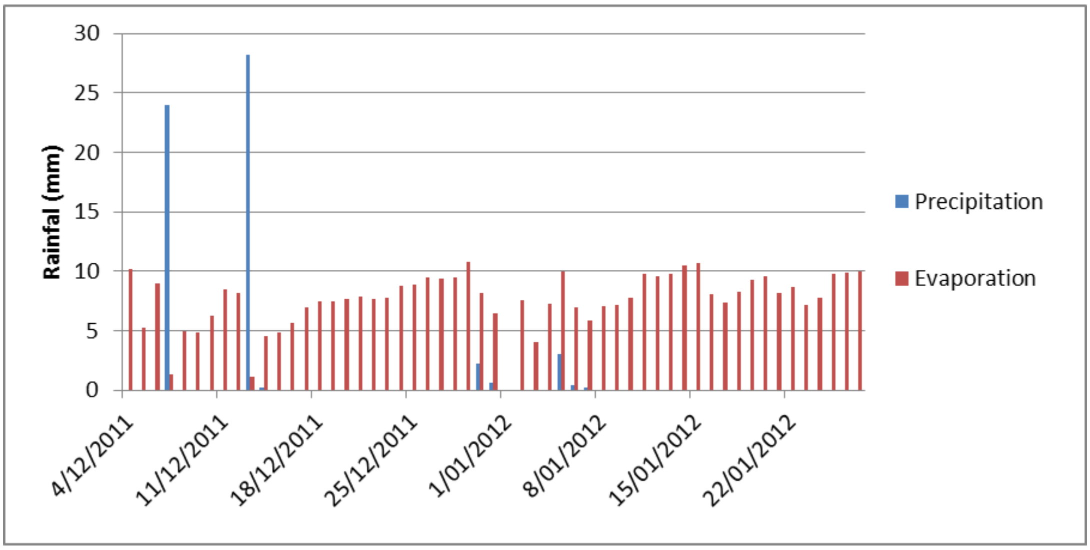

Figure 5-20: Rainfall and evaporation data recorded at the Myalup weather station for investigation C003.

Rain gauge data

Data from the rain gauge at C003 illustrates the two high rainfall events occurring in the carrot summer crop over the investigation period (04/12/2011-27/01/2012, Figure 5-21).

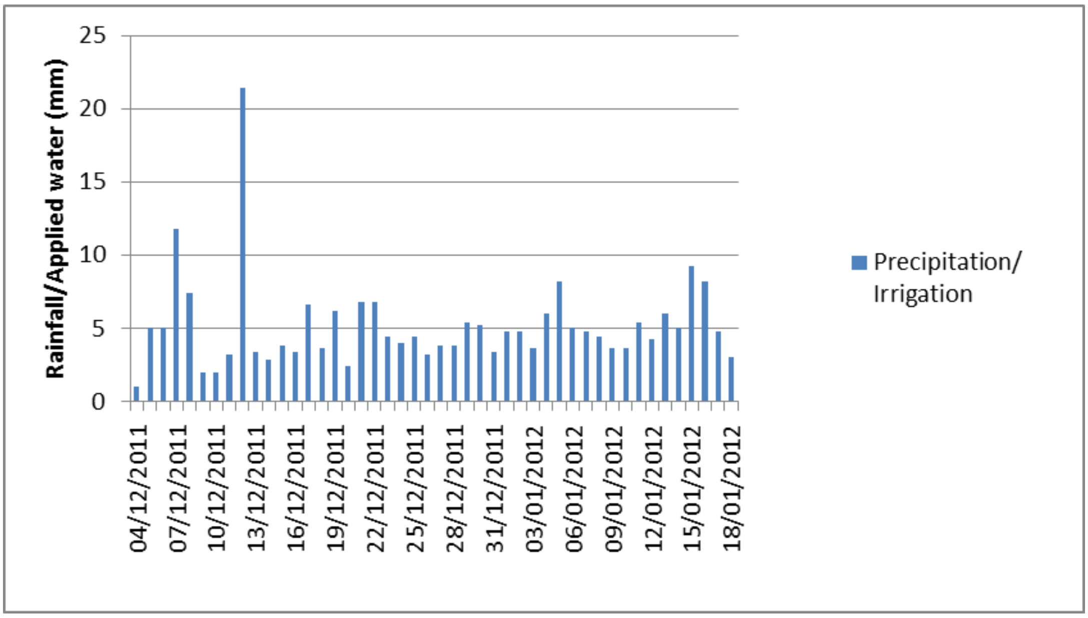

Figure 5-21: C003 crop precipitation/irrigation results.

C003 precipitation and irrigation

Figure 5-22 provides a comparison of the in situ rain gauge data and rainfall recorded at the nearby Myalup weather station. The graph differentiates between days in which rain fell and days in which sprinkler water was applied. Data between 18/01/12 and 27/01/12 were lost as a result of an error in the data logger. Observed differences in the volumes of rainfall recorded by the Myalup weather station and the rain gauge are attributed to the same reasons stated in the winter investigation.

Total Myalup rainfall was recorded at 58.8 mm and total crop precipitation/irrigation recorded by the rain gauge was 379 mm to 19/01/2011. Given these results, the total applied water to the crop for the investigation period was 320.2 mm. Thus rainfall comprised approximately 15 per cent of total precipitation and applied water 85 per cent.

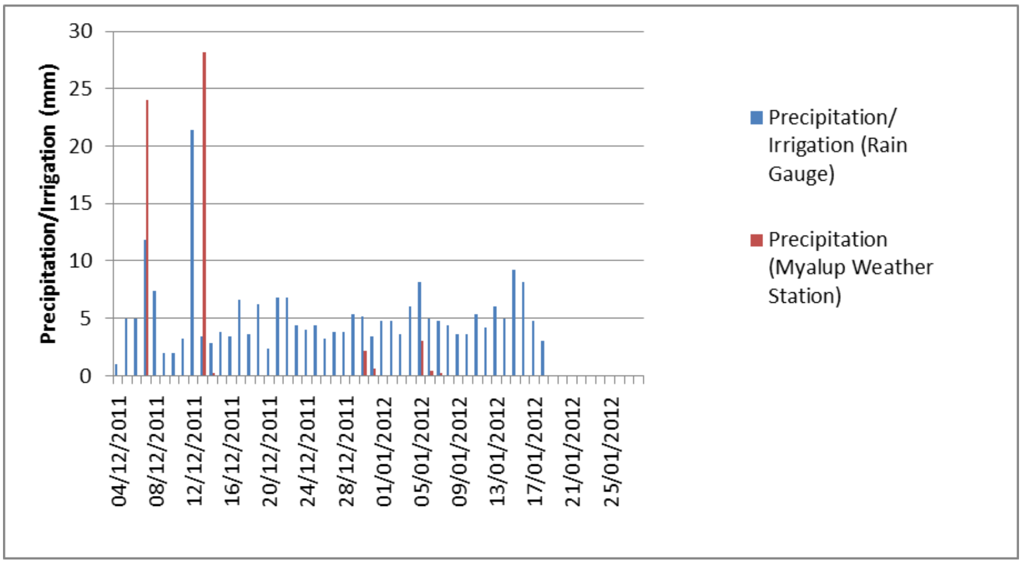

Figure 5-22: Rain gauge data from the Myalup weather station differentiates precipitation and irrigation.

Sprinkler applications occurred daily during the C003 investigation and their duration varied from between 60 and 75 minutes between 07:00 and 12:00 hours.

Horticultural managers strive to apply 10–11 mm of irrigation water daily (even on rainy days). So assuming 10–11 mm of sprinkler water during a one-hour period, the difference between applied water and daily rain gauge records can be attributed to the high evaporation rates experienced during the summer months (Figure 5-23).

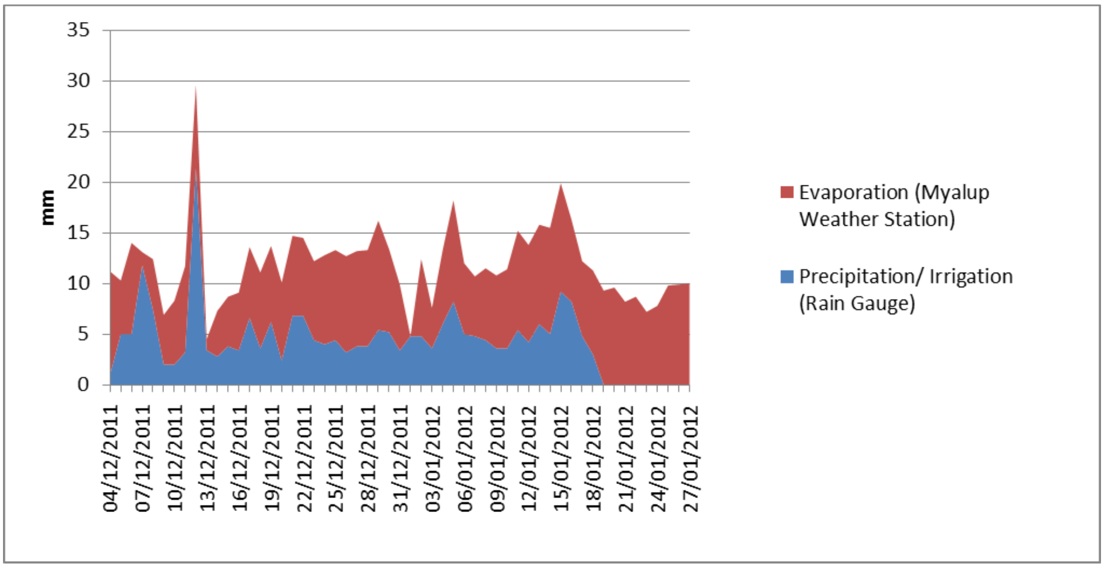

Figure 5-23: Rain gauge data and Myalup pan evaporation.

The data indicates the difficulty irrigators have in supplying sufficient water to the crops in excess of evaporation and that, on most days, 11 mm supplied at the sprinkler head is not realised at the crop surface. It also shows that in most instances the applied water received at the crop surface is less than the recorded evaporation.

Rainfall intensity and duration

Two rainfall events were recorded during the C003 investigation and a further 3 mm of rainfall was recorded at the Myalup weather station on the 05/01/12. Irrigation water was applied simultaneously (Table 5-5).

Table 5-5: C003 rainfall event summary.

Date	Event	Crop precipitation (mm)
07/12/11	D	18.8
12/12/2011	E	34.2
05/01/2012	F	13.1

For the purpose of this investigation the rainfall event occurring on the 12/12/2011 was selected for further analysis and the intensity of hourly rainfall for this day is given in Figure 5-24.

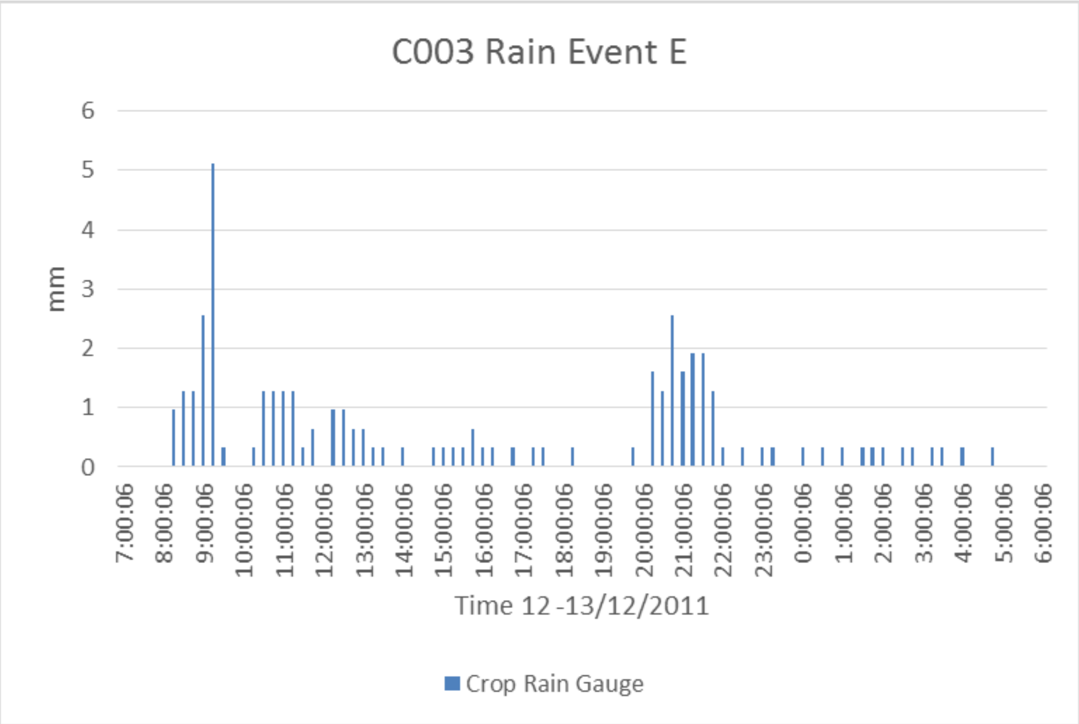

Figure 5-24: C003 rainfall Event E.

The graph demonstrates the intensity and duration of the applied water by rainfall. Importantly, this graph presents not just the daily rainfall volume but the intensity with which it falls.

5.2.2 Soil water content

Gravimetric soil moisture

The gravimetric soil water content through the profile was representative of the time of day that the samples were taken and the maturity of the crop (Figure 5-25). It also demonstrates the range of soil moisture expected during the summer growing season. As a result of the horticultural managers preference to irrigate early in the day, samples were often taken after irrigation water had been applied. Thus the following observations were recorded with the results:

- 04/12/2011 – sampling conducted approximately one hour after irrigation.
- 11/12/2011 – sampling conducted approximately 30 minutes after irrigation.
- 20/11/2011 – sampling conducted immediately after irrigation.
- 27/01/2012 – sampling conducted first thing in the morning with no irrigation since the previous day.

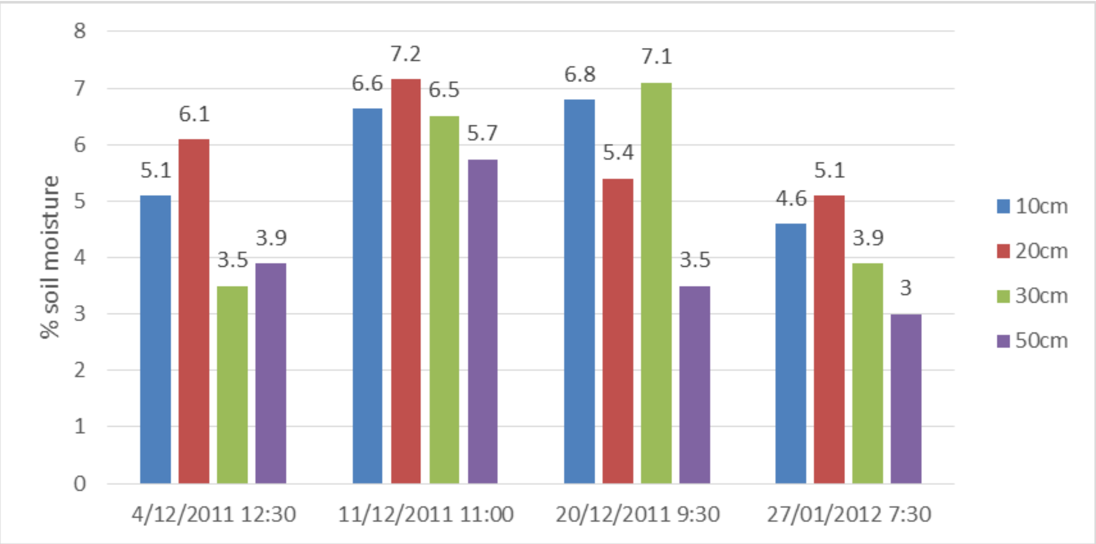

Figure 5-25: C003 Gravimetric soil water content.

5.2.3 Probe soil moisture

Uncalibrated soil moisture values for C003 illustrate effective infiltration through the 10-, 20-, 30- and 50 cm intervals down the profile in response to daily water (Figure 5-26). It should also be noted that during this period, the crop was maturing with associated soil compaction (Figure 5-27).

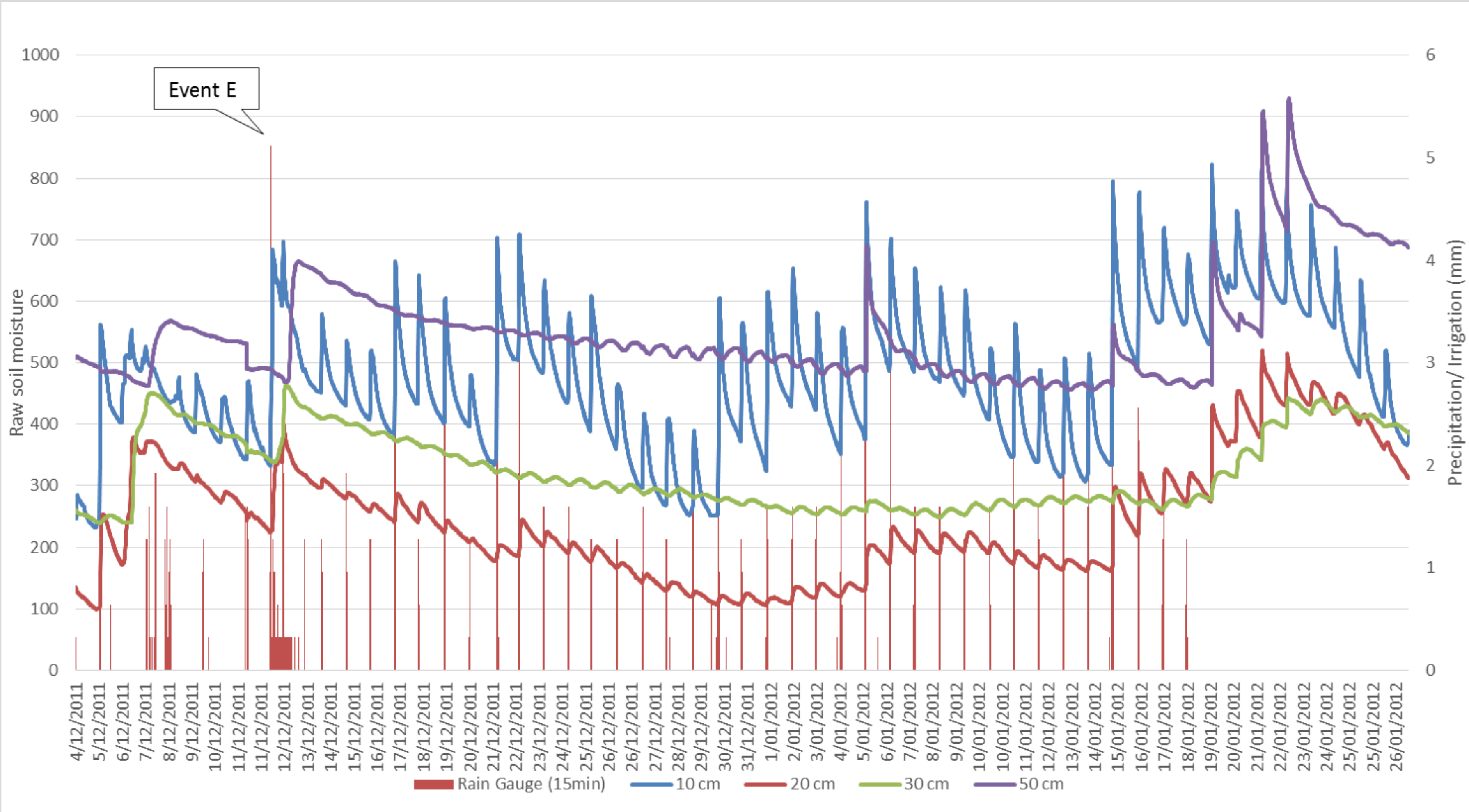

Figure 5-26: C003 soil moisture at 10-, 20-, 30- and 50 cm.

The summer data illustrate a similar escalation in soil moisture to the winter investigation (Figure 5-26) and six weeks into the investigation, an escalation in the four soil intervals was observed. Irrigation applications are evident by the sharp increase and decrease observed at the 10 cm interval. As noted earlier, there is a low holding capacity of the porous soil at this interval. Although not as extreme, the 20 cm interval showed corresponding increases in soil moisture as shown in the 20 cm interval curve.

Figure 5-27: Proximity of carrots within the soil profile illustrating soil compaction.

Rainfall events

The soil moisture data shows the 50 cm interval for the duration of the investigation and defines the occurrences of effective rinsing at that depth (Figure 5-26). As noted, equipment malfunction caused a data gap from 19/01/2012 to 27/01/2012. However, the weather station records indicate no rain fell during this period. It was assumed that daily irrigation water was applied at the same rate, thus the escalation in moisture should not be attributed to any increased amounts of irrigation water or rainfall.

Response to rainfall events

Figure 5-28 presents a graphical illustration of C003 soil moisture at the 10-, 20-, 30- and 50 cm intervals in response to rainfall Event D on 12/12/2011–13/12/2011. The C003 soil moisture graph shows soil moisture registered at the 50 cm interval at 02:30 on 13/12/2011 and rainfall for 12/12/2011 was 17.9 mm between 08:00 and 12:00. Moisture was initially registered at the surface and 20 cm interval with only a slight indication at the crop root 30 cm interval and no registration at 50 cm.

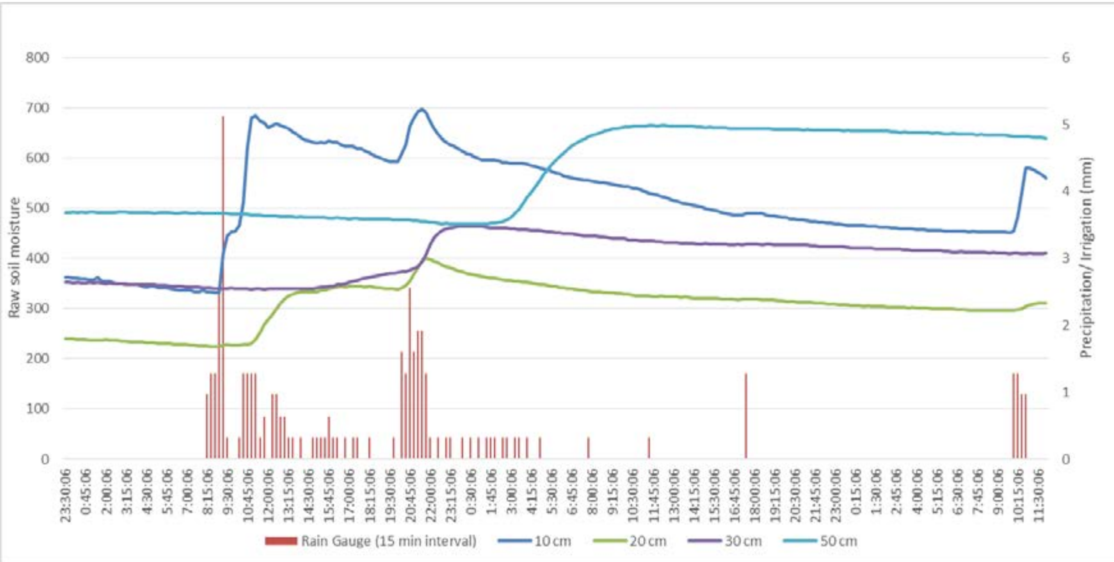

Figure 5-28: C003 soil moisture increases are shown at each interval down the soil profile in response to rainfall Event E.

Further rainfall received later during the evening on 12/12/2011 showed 12.8 mm between 20:00 and 22:00. This subsequent event was registered by the 20-, 30- and 50 cm, suggesting rinsing down the profile beyond the root zone. The soil moisture reading at the 50 cm interval registered at approximately 03:00 on 13/12/2011. Approximate moisture response times for Event E are given in Table 5-7 along with the time taken between intervals, excluding that at 10 cm.

Table 5-6: Moisture response times for rainfall Event E.

Interval (cm)	Time moisture detected (approx.)	Response from previous interval (mins)
10	08:45	×
20	09:15 and 11:00	60 mins
30	15:00	345 mins
50	02:30 (13/12/2011)	690 mins

Effective rinsing

The substantial summer rainfall event defined as Event E showed that rainfall infiltration extended through the soil profile to beyond the 50 cm interval.

5.2.4 Soil salinity

The effectiveness of this rinsing/dilution event is clarified by further examining the amount of root zone salts rinsed by the event. Soil samples were taken on 04/12/2012, 11/12/2012, 20/12/2011 and 27/01/2012 and analysed for gravimetric moisture, EC and net TDS (Table 5-7).

Table 5-7: C003 Soil salinity and associated soil moisture results.

Date	Interval (cm)	Gravimetric moisture (%)	Net EC µS/cm	Net TDS (ppm)
4/12/2011 12:30 WST	10	5.4	28,030	18,128
	20	6.5	18,986	12,291
	30	3.6	25,045	16,459
	50	4.1	6,062	3,903
11/12/2011 10:00 WST	10	7.1	12,102	7,745
	20	7.7	12,400	7,936
	30	7.0	13,304	8,514
	50	6.1	7,133	4,565
20/12/2011 09:30 WST	10	7.3	9,170	5,869

	20	5.7	16,801	10,753
	30	7.6	10,584	6,774
	50	3.6	8,294	5,308
27/01/2012 07:30 WST	10	4.8	19,389	12,409
	20	5.4	27,309	17,478
	30	4.1	29,178	18,674
	50	3.1	26,974	17,263

Note: µS/cm = microsiemens per centimetre. WST = Western Standard Time.

Crop soil salinity pre-rainfall and post-rainfall events

Rainfall Event D (07/12/2011) reduced salinity in the 10-, 20- and 30 cm intervals. However, there was an increase at 50 cm. Accumulated salts from the surface and crop root zone appear not to have fully percolated to the 50 cm interval (Figure 5-29).

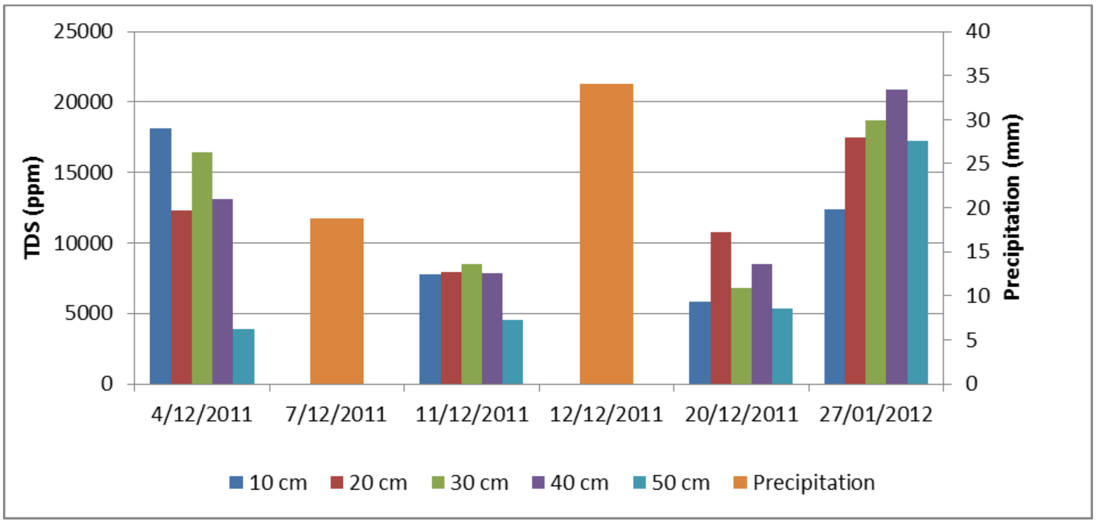

Figure 5-29: A reduction in soil profile salinity was observed subsequent to each rain event.

Rainfall Event E (12/12/2011) further reduced salinity in the 10 cm and 30 cm intervals and an increase in the 20 cm and 50 cm intervals was observed; indicating that salt had been rinsed down the soil profile but not necessarily rinsed out it.

No rain was recorded between 20/12/2011 and 27/01/2012, at which date this investigation ended and a large increase in salinity was observed across all intervals.

Salinity at the 50 cm interval was shown to increase throughout the investigation. Gravimetric soil moisture content for each sample is given in Figure 5-30.

Figure 5-30: Gravimetric soil water content plotted against salinity at each sampling event demonstrates the variation in soil water content of the soil samples taken.

Standardised soil moisture and salinity

Soil moisture and gravimetric data show that the moisture content varied markedly through the daily watering cycle from as high as 9.5 per cent of dry soil weight which approximates pore space saturation to 4.0 per cent. Assuming that the salt stays in situ, this indicates that the salinity of soil moisture varies substantially in response to percolation and evapotranspiration.

A standard value was calculated at three moisture percentages realistically representing the observed range of soil moisture content (4, 6 and 8%, Table 5-8). The data would appear to explain much about the soil moisture and TDS fluctuation in the crop. The samples taken on 04/12/2011 were prior to an irrigation application. It also shows that the salt appears to remain in the top 50 cm of the soil.

Table 5-8: Standardised TDS at 4%, 6%, and 8% moisture across all soil intervals

Date	Interval	Gravimetric Moisture %	TDS at			
			Actual	4%	6%	8%
4/12/2011	10	5.4	18,128	24,473	16,315	12,236
	20	6.5	12,291	19,973	13,315	9,986
	30	3.6	16,459	14,813	9,875	7,407
	40	3.2	13,093	10,474	6,983	5,237
	50	4.1	3,903	4,001	2,667	2,000
11/12/2011	10	7.1	7,745	13,747	9,165	6,874
	20	7.7	7,936	15,277	10,185	7,638
	30	7	8,514	14,900	9,933	7,450
	40	6.9	7,838	13,521	9,014	6,760
	50	6.1	4,565	6,962	4,641	3,481
20/12/2011	10	7.3	5,869	10,711	7,141	5,355
	20	5.7	10,753	15,323	10,215	7,662
	30	7.6	6,774	12,871	8,580	6,435
	40	4.5	8,511	9,575	6,383	4,787
	50	3.6	5,308	4,777	3,185	2,389
27/01/2012	10	4.8	12,409	14,891	9,927	7,445
	20	5.4	17,478	23,595	15,730	11,798
	30	4.1	18,674	19,141	12,761	9,570
	40	3.1	20,900	16,198	10,798	8,099
	50	3.1	17,263	13,379	8,919	6,689

TDS at 6 per cent soil water content

The calculated 6 per cent moisture is given in Figure 5-31 with the two rainfall events shown as D and E. This indicates the comparative TDS content at each profile interval that could have been expected to occur at some time during the watering cycle. The crop also received daily sprinkler irrigation of approximately 11 mm.

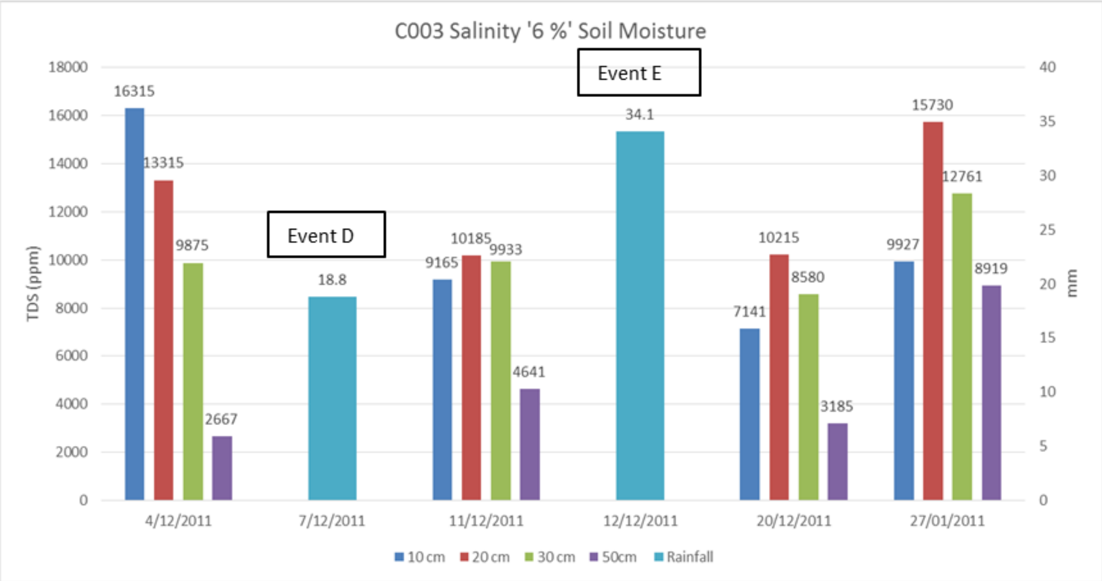

Figure 5-31: The response to rainfall events is shown to reduce salinity in the soil profile.

The 20 cm interval contained the highest average TDS (12,361 ppm). Data demonstrates the effect of the fortuitous summer rainfall events in reducing salinity in general and the absence of a rainfall event between 20/12/2011 and 27/01/2012 was coincident with the rapid escalation of salinity in the mature crop in mid-summer.

Measurement of TDS from collector trays, after the water had travelled from the sprinkler to the ground, showed an increase in TDS of 5–35%, depending on temperature, relative humidity and wind speed. Thus, in periods when the crop was under maximum evapotranspiration stress, the applied water had an effective TDS of 1,300 ppm and a reduced volume.

Accumulated salts without a rainfall event

In this case, the total crop precipitation/irrigation was 379 mm and total applied water 320.2 mm. Expected salts applied to the crop were calculated assuming TDS of the applied water during the summer to be 1,300 ppm (Meagher 2010) with 320 litres of applied water per m^2 crop = 3,200,000 litres per hectare (ha):

- g/L × 320 L = 416 g of salt per m2 = 4.16 tonnes salt per hectare.

A summary presenting the percentage increase and/or decrease in TDS at a calculated 6 per cent soil moisture is given in Table 5-9.

Table 5-9: Percentage increase or decrease TDS post-rainfall.

Interval (cm)	04/12/11–11/12/11 (post-rain) +/– (%)	11/12/11–20/12/11 (post-rain) +/– (%)	20/12/11–27/01/12 (no rain) +/– (%)
10	–44	–22	+39
20	–24	+0.3	+54
30	+0.6	–14	+49
50	+74	–31	+180

Salinity thresholds

Figure 5-30 shows the soil salinity results during the investigation period against the yield threshold values for carrots given by PIRSA (2007, Table 5-10). Data from this study determined that TDS levels at all four intervals on 04/12/2011exceeded the 50% limits (Figure 5-32).

Table 5-10: Yield threshold values for carrots.

Yield	100% (EC/TDS)	75% (EC/TDS)	50% (EC/TDS)
Carrot	2,000/1,280	5,800/3,710	9,200/5,890

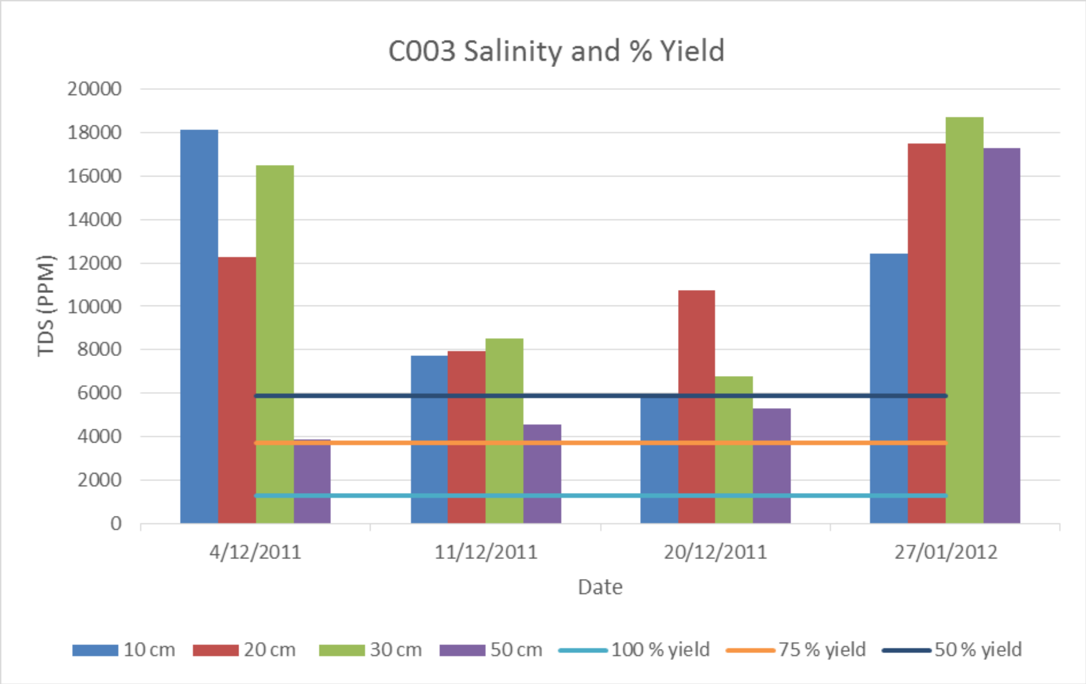

Figure 5-32: Soil TDS observed during the investigation shows that exceedances of recommended yield threshold values.

There was a reduction in TDS on 11/12/2011 after rainfall Event D. However, exceedance of the 50% yield threshold for the 10-, 20- and 30 cm intervals still occurred, while TDS at the 50 cm interval (beyond the crop root zone) was between the 50% and 75% yield limits.

After further rainfall (i.e. Event E) on 20/12/2011, further reduction in soil salinity was also observed. Exceedance of the 50% threshold was seen in the 20 cm and 30 cm intervals and the 10 cm and 50 cm intervals were between 50% and 75%. On 27/01/2012, all intervals exceeded the 50% limits.

Figure 5-33 to Figure 5-35 display the standard interval salinity calculated at 4%, 6% and 8% soil moisture reflecting levels representative of the lowest, average and highest moisture values observed.

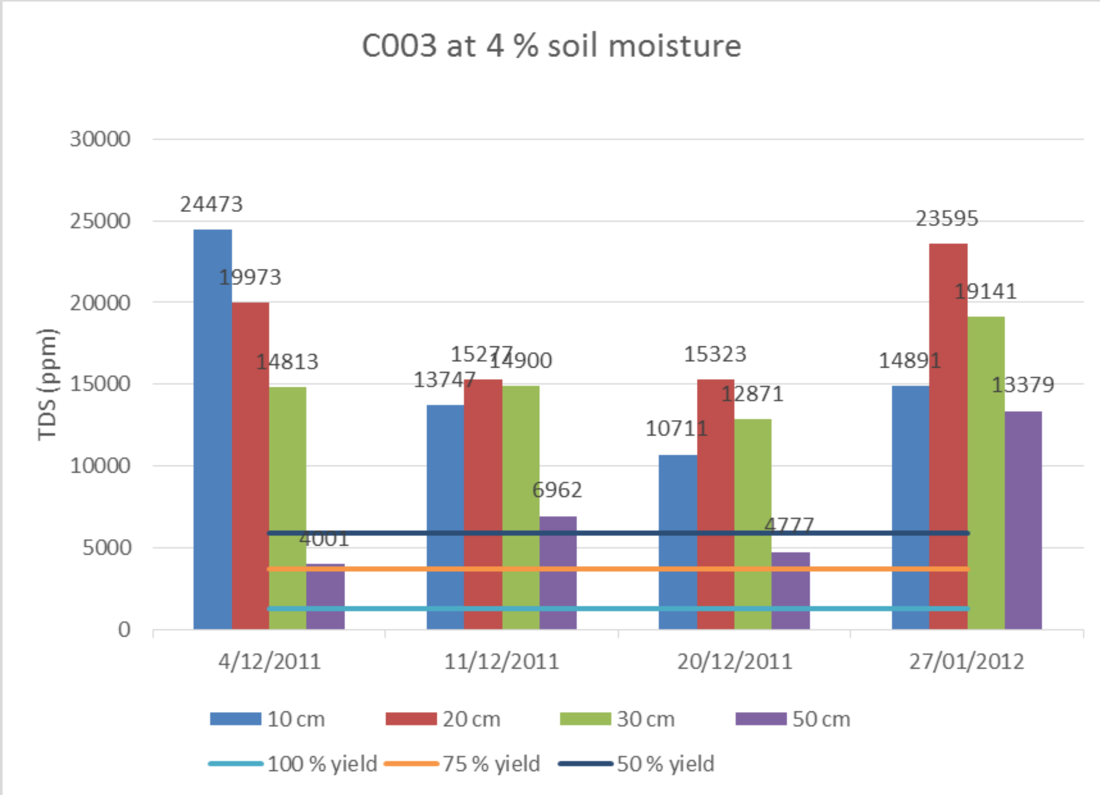

Figure 5-33: TDS levels and yield expected at 4 per cent soil moisture reflects the lowest soil moisture content observed reached during periods of high ET demand.

TDS calculated at 4% soil moisture provides indicative results for the lowest expected soil moisture readings and indicates the effect of shrinking soil water volume with consequential increased salt concentration in available soil water. At this TDS level all crop growing intervals exceed the 50% threshold and only the 50 cm interval on 04/12/2011 and 20/12/2011 remained within the 50% threshold.

Figure 5-34 presents the standardised TDS for 6% soil moisture at each interval and indicates an exceedance of the 50% threshold for the growing period at the 10-, 20- and 30 cm intervals throughout the duration of the investigation.

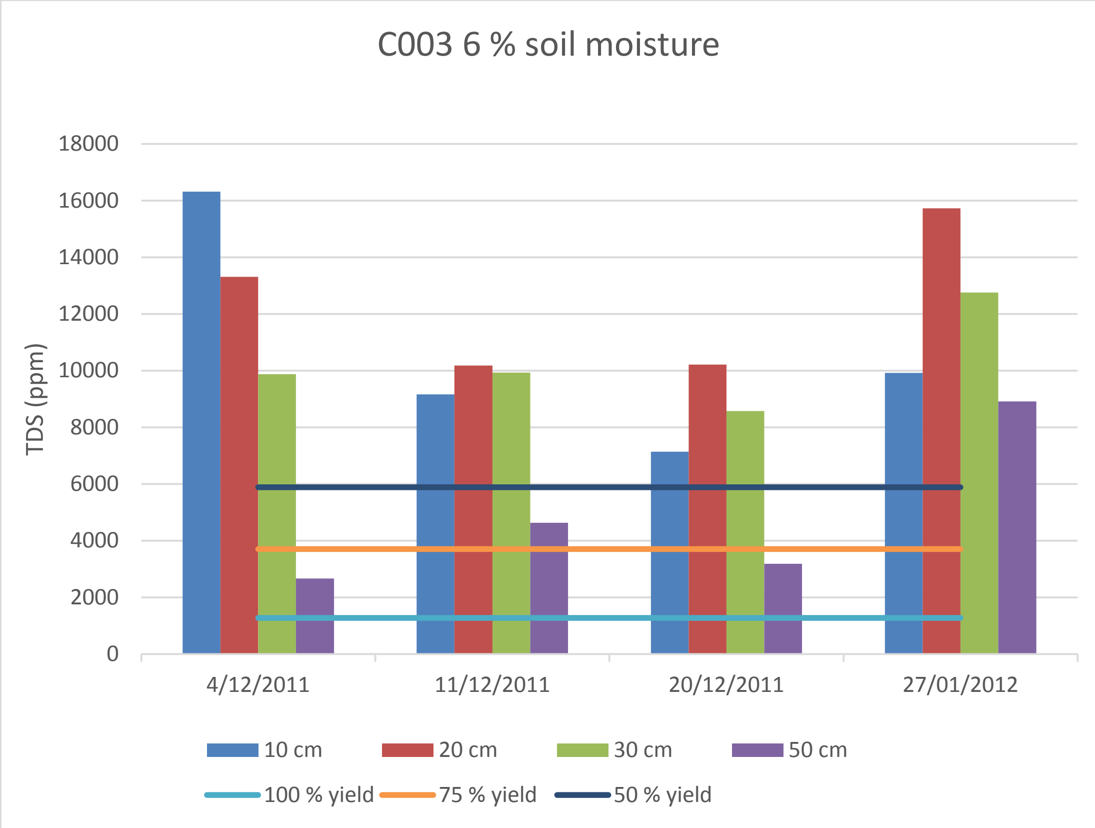

Figure 5-34: TDS levels and yield expected at 6 per cent soil moisture.

The 50 cm interval only exceeded the 50% threshold on 27/01/2012 and no rainfall event occurred between 20/12/2011 and 27/01/2012. This demonstrates the importance of maintaining moisture levels above 6 per cent between the surface and 30 cm intervals. Further analysis was conducted by applying the calculated 8% soil moisture to the results and are presented in Figure 5-35.

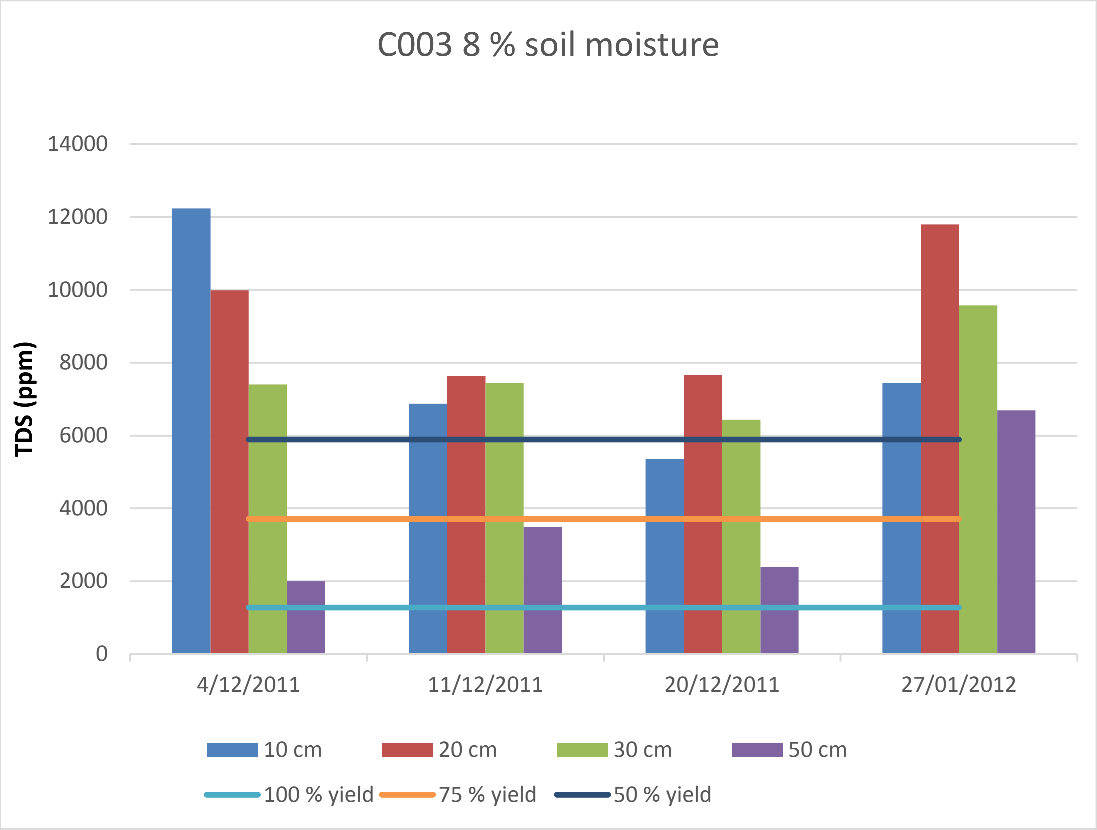

Figure 5-35: Shows TDS levels and yield expected at 8 per cent soil moisture.

Expected crop salts

The general trend was that, in summer, the occurrence of rainfall reduced the soil TDS at all levels while its absence had the effect of increasing it across all levels (Table 5-11). Escalating TDS also aligns with the general escalation in soil moisture across all intervals towards the latter period of the investigation.

Table 5-11: Expected total salts in the soil profile (ppm) at calculated soil water content.

Date	Observed	4%	6%	8%
04/12/2011	50,781	63,259	42,173	31,630
11/12/2011	28,760	50,885	33,924	25,443
20/12/2011	28,704	43,682	29,121	21,841
27/01/2012	65,824	71,006	47,337	35,503

5.3 Groundwater Quality

5.3.1 Irrigation water quality

The source water W1 pond was centrally located with observed TDS levels that ranged from 832 to 906 ppm during 2011 (Figure 5-36).

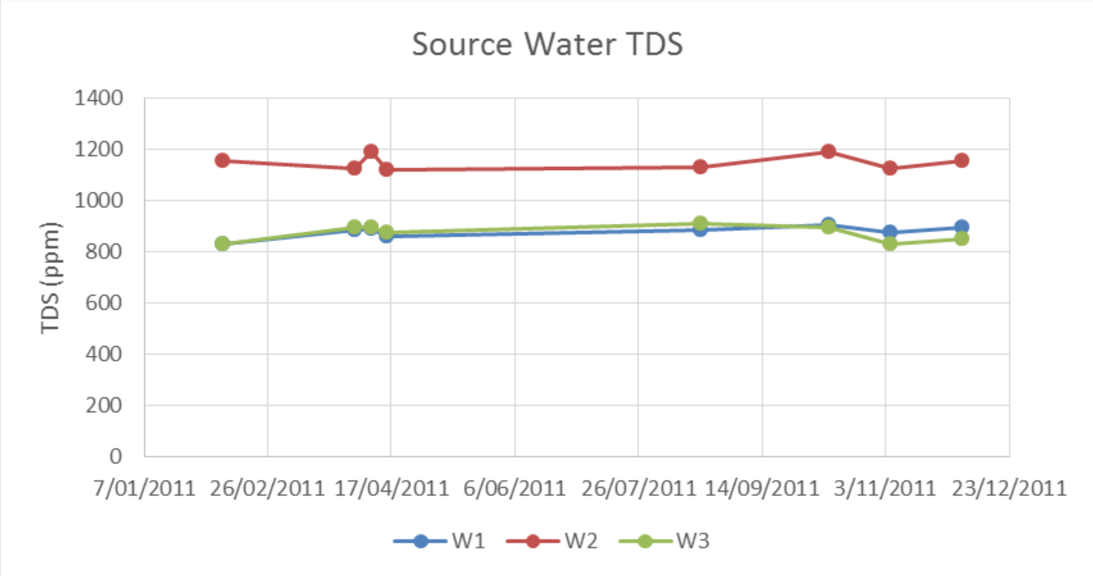

Figure 5-36: TDS at W1, W2 and W3 shows the stability of TDS levels in the irrigation source water throughout the investigation period (see Figure 3-1 for locations).

TDS at W3, located at the southern end of the horticultural property ranged from 829 to 911 ppm, was very similar to W1. In contrast, TDS at W2 was consistently higher than both W1 and W3 (1,119 to 1,187 ppm) during the same period. W2 is located 550 m from W1 and approximately 1.2 km from W3.

Laboratory analyses

Laboratory analyses, routinely undertaken by the horticultural property management, were carried out during the investigation period at W1, W2, W3 and MB2 on 08/02/2011 and 11/10/2011 (Figure 5-37). Data indicated that TDS levels of the irrigation source water at MB2, before it passed beneath the horticultural property, were considerably lower than those at W1, W2 and W3.

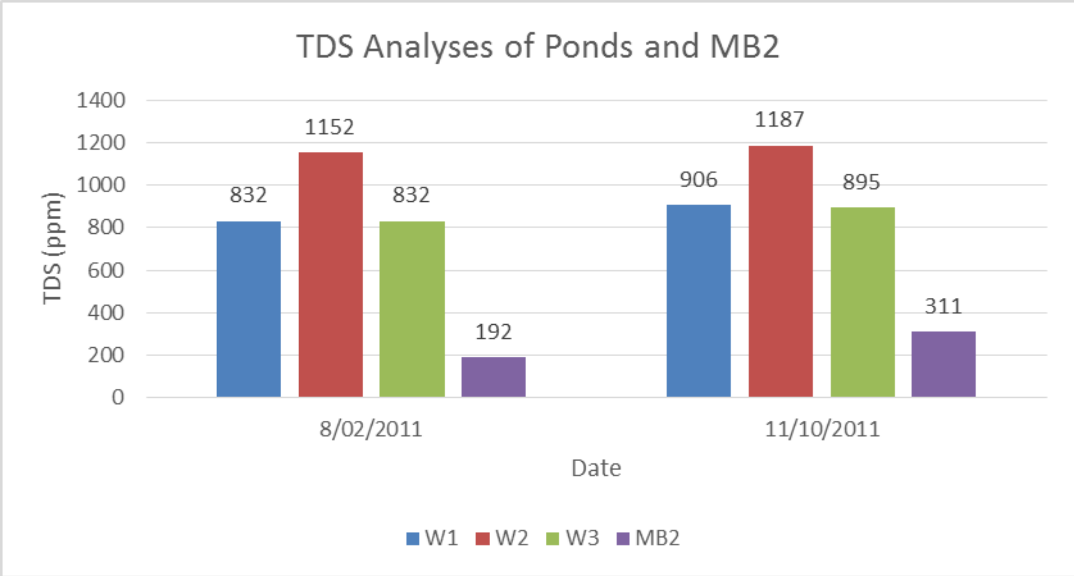

Figure 5-37: Laboratory analyses of W1, W2, W3 and MB2.

Nitrogen values at W1, W2, W3 and MB 2 taken on 08/02/2011 are provided in Figure 5-38 and indicate that nitrogen returning to the groundwater underlying the crops has little effect on the observed TDS of the groundwater supply.

Nitrogen levels at MB 2 indicate the TDS of groundwater at the eastern boundary of the property, prior to it moving under the cropped area and becoming available as irrigation source water.

The nitrogen levels show differences in water sources across the property. The centrally located W1 water source shows elevated nitrogen levels of W2, at the north western edge of the property.

MB2 is considerably lower than the three ponds, as was shown in Figure 5-37 with regards to TDS.

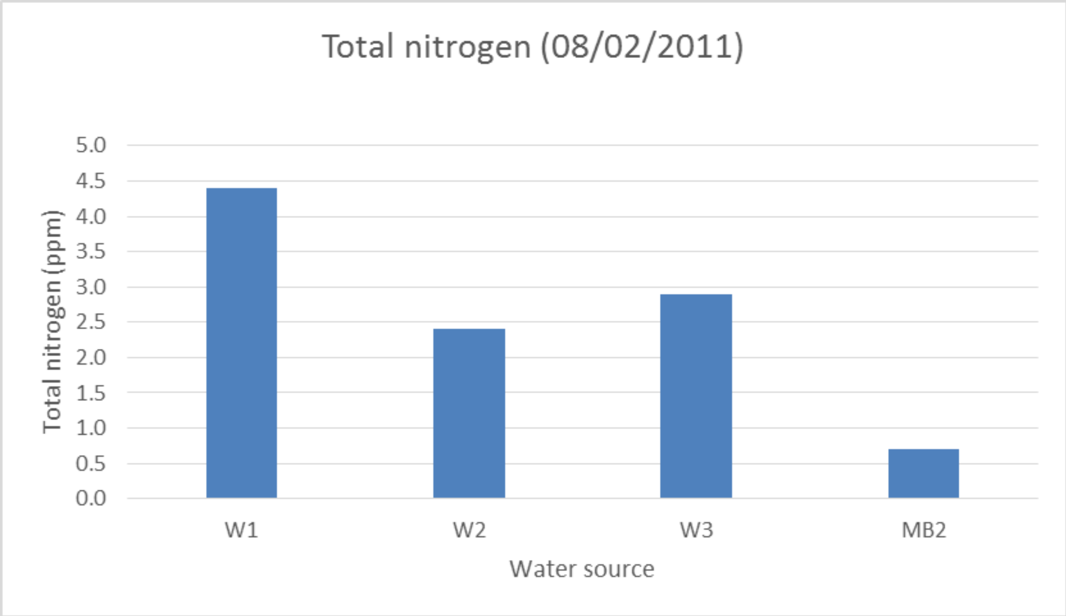

Figure 5-38: Total nitrogen at W1, W2, W3 and MB2.

C003 Irrigation water salinity

During the C003 summer investigation, irrigation water was collected in pans placed among the crops and this was undertaken to assess evaporation and changes in TDS that occurred between the sprinkler head and the ground. Analysis indicated that TDS increased with evaporation (Table 5-12).

Table 5-12: Evaporation calculated on 27/01/12.

Date	Time	Temperature (°C)	Source water	Observed TDS (at ground)	Evaporation
27/01/12	07:30	30.9	840	1,154	24 %
	08:30	33.4	840	1,124	22%
	10:30	34.2	1,150	1,341	20 %
	11:30	35.4	1,150	1,529	24 %

CHAPTER 6. DISCUSSION

The original scope of this research was to determine if seasonal rainfall in Binningup was sufficient to effectively rinse the soil profile of salts and replenish the irrigation source water to sustain horticultural activities. It was also envisaged that this information would allow horticultural managers to develop an optimal regime of summer irrigation for salt reduction, fertiliser efficiency and crop yield. There were three main objectives:

- To record the behaviour of both rainwater and sprinkler water in the crop soil profile in response to the age of the crop and ambient meteorological conditions
- To record salt accumulation from sprinkler water in the soil profile and determine the intensity and duration of rainfall required to rinse water from the soil profile.
- To determine the replenishment of the aquifer below the crops and conclude whether there was significant accumulation of salt in the upper portions of the aquifer.

The primary results from this investigation have indicated the following:

- Accurate volumes of applied water and rainfall were measured and a known quantity of salt was added to the crop.
- Soil moisture measurements indicated a number of rainfall events occurred sufficient enough to saturate the soil at the 50 cm interval.
- Soil water salinity was measured and indicated that a reduction in salinity occurs after rainfall events that saturate the 50 cm soil profile in summer and winter.
- Average annual rainfall does not affect the quantity of groundwater available for irrigation.
- Salts are returned to the groundwater below the crops; however, groundwater is replenished sufficiently for irrigation purposes.
- Nitrogen as an indicator of groundwater contamination has a negligible effect on irrigation water salinity

And these are discussed in turn below.

6.1 Crop precipitation

It is known, through volumes of water extracted (via pumping capacity and hours), that the horticultural managers aim to apply between 10 and 11 mm of water to the crops each day during summer. However, rain gauge data for the summer investigation period showed that on average, 7.1 mm is received daily at the crop surface. Clearly factors contributing to evaporation are significant in adjusting desired delivery rates. Results from trials conducted on 27/01/2012 noted that evaporation between the sprinkler head and the ground was around 20-25% and this leads both a reduction in volume delivered and a concomitant increase in applied water salinity (Bavi et al. 2009; Uddin et al. 2014). Additionally during summer, water is applied to the crops daily. Whereas in winter, application rates are determined by a combination of crop stage, fertiliser application, rainfall and frost conditions (Table 6-1).

Table 6-1: Summary of P003 and C003 precipitation/irrigation and evaporation.

Investigation and season	Duration (days)	Total crop precipitation/irrigation (mm)	Total rain (mm)	Total applied water (mm)	Mean evaporation
P003 winter	85	597 (7 mm/day)	451 (5.3 mm/day)	146 (1.72 mm/day)	2.25%.
C003 summer	45	379 (8.42 mm/day)	58.8 (1.3 mm/day)	320.2 (7.2 mm/day)	7.75%

While average daily crop precipitation/irrigation was 8.42 mm in winter, compared with 7 mm in summer, it was the difference in evaporation (2.25% versus 7.75% respectively) that accounted for the requirement for additional volumes of applied water. For example, average daily water application received by the crop during P003 was 1.7 mm, very much less than during C003 (7.2 mm).

Rainfall in the year in which this research took place (931 mm) was above the six-year average for this area (802 mm, Figure 6-1.). Thus it would seem that this would need to be taken account of in any irrigation management plan.

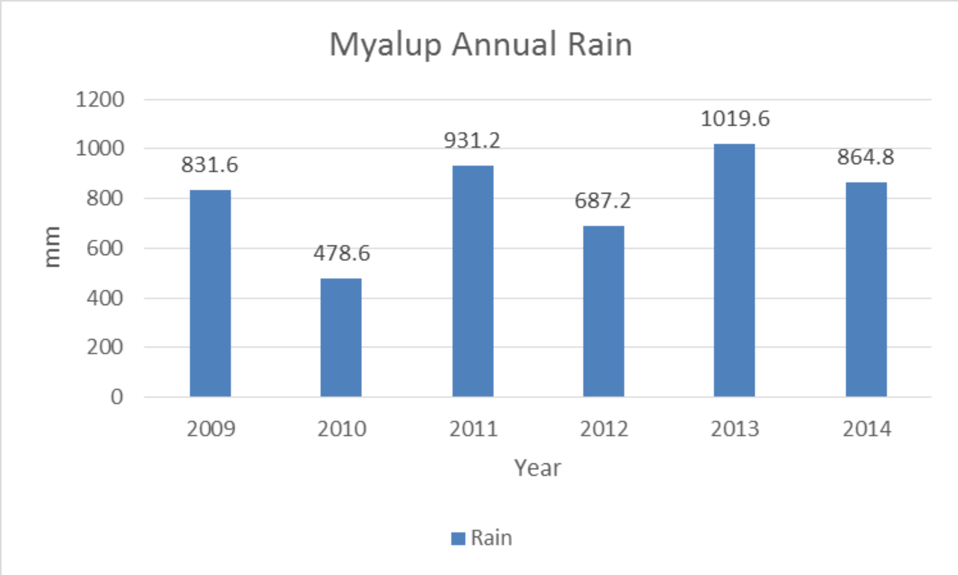

Figure 6-1: Myalup annual rainfall for years 2009–2014.

6.2 Soil moisture

The gravimetric soil moisture enabled the research to standardise the observed soil water salinity measured to greater understand the TDS levels expected at different levels of soil moisture. Gravimetric soil moisture for the winter (P003) investigation was generally high (4.1% to 8.3%). This may be attributable to low evaporation, low temperatures and the 49 days with rain occurring. This also underpins the requirement for small volumes of water to be applied during the winter growing season. This is in contrast with summer, where soil moistures ranged from 3.0% to 7.2% (averages across sampling events at 4.65%, 6.5%, 5.7% and 4.15%).

6.3 Natural rinsing

The primary focus of this investigation was to determine the effectiveness of the rainfall events in winter and summer to leach salts from the soil profile and this was determined by measuring the saturation at and below the root zone (Ayers and Westcot 1985; Monteleone and Libutti 2012). At Binningup this was at the 30 cm and 50 cm soil intervals and is illustrated by the sharp increase and decrease of the curve for the interval on the soil moisture graphs (Figure 5-11, 5-12 and 5-26).

To ensure the sustainability of horticultural activities, salts must be rinsed past the 30 cm interval, the 50 cm interval and through to the underlying superficial aquifer (Barnard et al, 2010; Platts and Grismer 2014). Encouragingly, the three events analysed during winter and one event during the summer indicated that this had occurred. Significant summer rainfall events and summer irrigation have little effect on reducing salinity values as compared with seasonal rainfall experienced in winter, as was observed by Biswas et al. (2009).

6.3.1 Escalating soil moisture

Soil moisture recorded in both winter and summer investigations indicated that there was an escalation in soil moisture in the latter crop stages. No increase in crop precipitation and/or irrigation was recorded to suggest that it was responsible for the escalation. Additionally, no anomalous evaporative conditions were recorded either.

In P003, the escalation occurred on 18/07/2011, 51 days into the investigation, which is approximately when the crop was planted. At C003 the investigation started in a juvenile crop, where small vegetables were already present at the sensor location. An escalation in soil moisture was observed on 16/01/2012, 43 days into the investigation. Evidence of vegetable growth and density increased was observed in both P003 and C003 at these stages and escalation of the crop soil moisture was noticeable for P003 at the 10 cm and 20 cm intervals and in C003 at the 10 cm, 20 cm and 30 cm intervals. It can be concluded that the escalation in crop soil moisture may be attributed to the following:

- **Compaction of the tilled surface soil due to precipitation**. This was evident after heavy rain events in P003, where the tilled rows were observed to appear more compressed (Shainberg and Letey 1984; Imeson and Kwaad 1990; Batey 2009) and where soil appeared to have splashed on to the side of the in situ instruments. This was noticeable in the earlier stages of the investigation when there was an absence of vegetable foliage.

- **Vegetable growth and proximity**. An increase in vegetable growth and proximity was observed which compacted the soil in between, and surrounding, the vegetables (Gregory 2006). The effect of the soil compaction was to increase its water-holding capacity (Hamza and Anderson 2005). Subsequently, a greater proportion of crop precipitation/irrigation water was retained at these intervals

(Figure 5-11, 5-12 and 5-26). As the potatoes were grown further up in the profile, this corresponded with the increased soil moisture in the 10 cm and 20 cm intervals. Likewise, the increase in soil moisture at the 10 cm, 20 cm and 30 cm intervals of the C003 carrot crop corresponds with the depth that the carrots were grown.

- **Proximity of probe sensors to vegetables**. It was observed that the soil moisture probe sensors were close to the surrounding vegetables as the crop matured. This may have had the effect of recording the moisture that was held within the vegetables, as sensors may have a strong correlation with organic material (Fares et al. 2016) and it is known that potatoes contain approximately 70–80% water and carrots 85–90%.

Therefore, if the moisture holding capability or bulk density of the crop soil increases with crop maturity, it may reduce the effectiveness of a rain event to leach or dilute crop root zone salts, particularly during low volume, low intensity rain events. Similarly, the volume of rainfall observed to be effective in reducing TDS in the earlier stages of the crop may not be as effective in reducing crop TDS in the later stages.

The ability for horticultural managers to maintain the required soil moisture is therefore increased toward the later stages of crop development and may be beneficial in terms of water use and water efficiency.

6.4 Salinity

It can be concluded that measuring soil water salinity is integral to determining the effectiveness of the rainfall events to rinse the soil profile. Records of salt concentration at each interval pre- and post-rainfall, indicated the downward movement of salts below the crop root zone. Soil water salinity measured at P003 was shown to increase with the development of the crop. This was also observed in C003.

Salts are added to crop soils with each irrigation application (Oster 1994). Therefore, a known quantity of salts is calculated for each investigation period. It was calculated that a total of 0.8 tonnes of salt per hectare was added to P003 during the winter investigation through the application of irrigation water. It is estimated 4.16 tonnes of salt per hectare was added to C003 during the summer investigation.

Note however, that P003 had 451 mm total rainfall and four events that saturated the 50 cm interval. While C003 had 58.8 mm total rainfall in two events that effectively saturated the 50 cm interval. In addition, the TDS concentration of the applied water was shown to increase through evaporation between the sprinkler head and the ground (Lantske et al. 2007).

It was shown in Figure 5-33 that salts applied with irrigation applications from 04/12/2011 to 11/12/2011 and from 11/12/2011 to 20/12/2011 were effectively rinsed with rainfall events that occurred on 07/12/2011 and 12/12/2011 respectively. These events had the effect of reducing salts at all intervals with the exception of the 30 cm interval on the 11/12/2011 where a minor increase (58 ppm) was recorded and a substantial increase was shown at the 50 cm interval (1,974 ppm). These results were recorded after five days of subsequent irrigation applications.

It can be concluded that the rainfall event on 07/01/2012 did not compromise the required volume to leach the salts passed the 50 cm interval, thus leaving an accumulation of the leached salts at this depth. Also a minor increase (30 ppm) was shown to occur at the 20 cm interval on the 20/12/2011 following eight days of applied water after the rainfall event.

A reduction in TDS levels at the 50 cm interval shows that the volume and intensity of the rainfall on 12/12/2011 was sufficient enough to leach the accumulated salts below the 50 cm interval and to the underlying aquifer. The minor increase in the 20 cm interval can be attributed to the salts applied with the subsequent eight days of irrigation water.

6.4.1 Salinity and yield

Soil moisture and gravimetric data show that moisture content varied markedly through the daily watering cycle from as high as 9.5 per cent of dry soil weight which approximates pore space saturation to 4.0 per cent. Assuming that the salt stays in situ, this indicates that the salinity of soil moisture varies substantially in response to percolation and evapotranspiration (Jackson 1973: Villagarcía et al. 2004). Therefore a standard for soil moisture was applied to indicate expected TDS concentrations at a range of soil moisture conditions reflective of those observed during the course of the investigations. These were 4%, 6% and 8 %.

The results indicate that the 100 per cent threshold level is exceeded at all levels at the 4%, 6% and 8% calculated soil moisture for the summer investigation period. At 8 per cent calculated soil moisture, the 50 per cent threshold was exceeded by all intervals at each sampling event with the exception of the 50 cm interval on 04/12/2011, 11/12/2011, 20/12/2011 and the 10 cm interval on 20/12/2011.

These results indicate that rainfall events greater than 30 mm during winter or summer have the ability to saturate the soil profile to depths below the crop root zone and effectively leach or dilute the soil water of accumulated salts.

6.5 Groundwater quality

Groundwater enters the east of the property at a salinity of 200 to 300 ppm (Meagher 2010) and total nitrogen between 0.5 and 1.0 ppm. It generally flows in a westerly direction beneath the property (Rockwater Pty Ltd. 2000). Irrigation water and rainfall percolates through the crop soil which results in the return of irrigation water and associated salts to the groundwater (Lantzke 1997).

This is demonstrated by the occasional increases in nitrogen and TDS at W1 which is central to the cropped area (Figure 3-1) and therefore represents a good indicator of groundwater quality underlying the property. TDS levels at W1 were observed to range from 832 to 906 ppm.

While W3 TDS levels were similar to W1, TDS at W2 was 200–300 ppm higher (~1,200 ppm). The reason for this variation in TDS may be explained by the effect of the previous land uses on the Coastal Limestone and the reaction of the groundwater to heterogeneous characteristics within the formation, however these factors were not within the scope of the research.

Nitrogen recorded at W1, W2, and W3 as an indicator of groundwater contamination from fertiliser applied to crops during the growing season did not increase the TDS of the groundwater supply.

TDS levels monitored at W1 remained stable, despite recirculation of the irrigation water and the salts found to be accumulating in the soil profile during the summer growing period. The return of salts to the groundwater did not register unsustainable levels, suggesting that there was adequate mixing of the returned irrigation water and the underlying source water. This is confirmed by past TDS records (Meagher 2010) which show that levels remained stable during the past 10 years of horticultural operations. It can therefore be concluded that the current horticultural practice is sustainable in the long term.

CHAPTER 7. CONCLUSION

At Binningup–Myalup, the near-surface superficial aquifer contains a greater volume than that required for sprinkler-irrigated vegetable crops. However, the combination of high TDS, good drainage and high evapotranspiration cause the soil water salinity to be limiting to yield. Additionally, the practice of maintaining irrigation water at the crop root zone, while preventing leaching of fertilisers, allows salts to accumulate to levels prohibitive to sustainable yield during summer months. Evaporation of applied water between the sprinkler and the crop was recorded to be up to 25% in summer months resulting in a reduced volume of applied water and increased salinity. It was also observed that the target of 10–11 mm of applied water was often not achieved.

The physical characteristics of the soil overlying the property enabled 100% infiltration and a combination of crop precipitation/irrigation and soil moisture measured during the winter and summer investigations found that rainfall events in excess of 30 mm were sufficient to saturate the soil profile to depths of up to 50 cm for the duration of the investigation. These rainfall events provide a natural mechanism to transport solutes below the crop root zone during the growing periods. A change in crop soil moisture characteristics was also observed during the crop cycle and soil moisture escalated in the top 20–30 cm of the soil profile during the latter stages of potato and carrot crop development.

It was shown that levels of soil water salinity during a winter potato crop were below the recommended 100% yield threshold value. Thus with these greater volumes of rain and low evaporation, the accumulation of salts in the crop root zone pose no concerns for horticultural managers during the winter growing season.

However, root zone soil water salinity measured on a summer carrot crop were found to exceed the recommended 50% yield threshold value at four routine sampling events during the course of the growing period. Furthermore, the TDS concentrations at a calculated soil moisture content of 8% were also found to exceed the recommended 50% yield threshold values. Therefore, during the summer growing season, it is recommended to maintain crop soil moisture at levels greater than 8% to prevent major yield reduction or crop loss.

Rainfall events analysed during this research were found to rinse the crop soils of accumulated salts applied during irrigation. It must be noted that crops grown during the winter period and subject to rainfall events above 30 mm are not affected by accumulating salts. It is also recommended that crops grown in the summer period should be located on areas of the property that have remained bare during the winter months. This would ensure that the soils have been rinsed of salts from previous crops and associated irrigation.

Data collected from this research indicates that crops grown in the summer months require at least one rainfall event >30 mm to reduce the effect of accumulating crop salts applied by overhead sprinkler irrigation. For example, the exceedance of the 50% yield threshold value at 8% calculated soil moisture indicates that summer crops may not be sustainable without further intervention or alternative irrigation strategies such as applying appropriate volumes of irrigation water. Although this was outside of the scope of the current study it may prove fruitful for future investigations.

To conclude; this research evaluated the effect of annual rainfall against intensity and frequency of rainfall events in determining the sustainability of horticulture in relation to sprinkler irrigation water, salinity increase and weather regime. Results indicated that it is the occurrence of high-volume, short-duration rainfall events that enhance salt rinsing, as opposed to consistent low volume application by rain or reticulation. During intense rainfall events, excess water results in reducing soil salinity by rinsing the salts accumulated past the crop root zone and into the underlying superficial aquifer. Thus, it is not whether winter rainfall is above or below average that regulates residual soil water salinity, rather the intensity and frequency in which it occurs.

REFERENCES

Allen, R.G., Pereira, L.S., Howell, T.A., & Jensen, M.E. (2011). Evapotranspiration information reporting: I. Factors governing measurement accuracy, *Agricultural Water Management*, Volume 98, Issue 6, 2011, Pages 899-920.

Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements*. Irrigation and Drainage Paper No. 56. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Arregui, L.M., & Quemada, M. (2006). Drainage and nitrate leaching in a crop rotation under different N-fertilizer strategies: Application of capacitance probes. *Plant and Soil*. 288(1/2), 57–69.

Ayers, R.S., & Westcot, D.W. (1985). *Water quality for agriculture*. Irrigation and Drainage Paper No. 29. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Barnard, J.H., van Rensburg, L.D., & Bennie, A.T.P. (2010). Leaching irrigated saline sandy to sandy loam apedal soils with water of a constant salinity. *Irrig Sci* 28:191–201.

Batey, T. (2009). Soil compaction and soil management – a review. *Soil Use and Management*, December 2009, 25, 335–345.

Bavi, A., Kashkuli, H.A., Boromand, S., Naseri, A., & Albaji, M. (2009). Evaporation losses from sprinkler irrigation system under various operating conditions. *Journal of Applied Sciences,* 9(3), 97–600.

Bilskie, J. (2001). *Soil water status: content and potential*. Retrieved from https://s.campbellsci.com/documents/us/technical-papers/soilh20c.pdf

Biswas, T., Bourne, J., Schrale, G., & McCarthy, M. (2009). *Salinity Management Practice Guidelines: Managing root-zone salinity for irrigated horticultural crops in winter rainfall zones of Australia*. National Program for Sustainable Irrigation Land & Water Australia, Canberra, ACT.

Black, C.A. (1965). Methods of Soil Analysis: Part I Physical and mineralogical properties. *American Society of Agronomy*. Madison, Wisconsin, USA.

Bolland, M. (1998). Soils of the Swan Coastal Plain. *Agriculture Western Australia*, Bunbury.

Cardon, G.E., Davis, J.G., Bauder, T.A. & Waskom, R.M. (2007). *Managing saline soils*. Retrieved from http://www.ext.colostate.edu/pubs/crops/00503.html.

Charlesworth, P. (2005). *Soil water monitoring: An information package*. (2nd Edition). Land & Water Australia on behalf of the National Program for Sustainable Irrigation.

Chen, D., Gao, G., Xu, C.-Y., Guo, J., & Ren, G. (2005). Comparison of the Thornthwaite method and pan data with the standard Penman-Monteith estimates of reference evapotranspiration in China, *Climate Research*, 28, 123–132.

Commander, D.P. (1988*). Geology and hydrogeology of the superficial formations and coastal lakes between Harvey and Leschenault Inlets (Lake Clifton Project).* Professional Papers Report 23, Western Australia Geological Survey, Hydrogeology Report 2605 (unpublished).

Cook, F.J., Jayawardane, N.S., Rassam, D.W., Christen, E.W., Hornbuckle, J.W., Stirzaker, R.J., & Bristow, K.L. (2006). *The state of measuring, diagnosing, ameliorating and managing solute effects in irrigated systems*. CRC for Irrigation Futures Technical Report, No. 04/06.

Cosh, M.H., Jackson, T.J., Bindlish, R., Famiglietti, J.S., & Ryu, D. (2005). Calibration of an impedance probe for estimation of surface soil water content over large regions. *Journal of Hydrology*, 311:49–58.

Critchley, W., Siegert, K., & Chapman, C. (1991). *A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production*. Food and Agriculture Organisation of the United Nations, Rome, Italy.

DAFWA – see Department of Food and Agriculture Western Australia.

Dastane, N.G., (1978). *Effective rainfall in irrigated agriculture*. Irrigation and Drainage Paper No. 25. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Department of Agriculture and Food Western Australia. (2015a). *Water salinity and plant irrigation*. Retrieved from https://www.agric.wa.gov.au/fruit/water-salinity-and-plant-irrigation?nopaging=1

Department of Agriculture and Food Western Australia. (2015b). *Carrots in Western Australia*. Retrieved from https://www.agric.wa.gov.au/carrots/carrots-western-australia

Department of Agriculture and Food Western Australia. (2015c). *Live automatic weather stations*. Retrieved from http://agspsrv34.agric.wa.gov.au/climate/livedata/sumpages.htm

Department of the Environment. (2015). Australia's bioregions (IBRA). Retrieved from http://www.environment.gov.au/land/nrs/science/ibra

Dodd, I.C., Egea, G., Watts, C., & Whalley, W.R. (2010). Root water potential integrates discrete soil physical properties to influence ABA signalling during partial rootzone drying. *Journal of Experimental Botany*. V61, 113: 3543–3551.

Ershadi, A., McCabe, M.F., Evans, J.P., & Walker, J.P. (2011). *Evaluation of energy balance, combination, and complementary schemes for estimation of evaporation*. IAHS Publ., 344, 52–56.

Ertek, A. (2011). Importance of pan evaporation for irrigation scheduling and proper use of crop-pan coefficient (Kcp), crop coefficient (Kc) and pan coefficient (Kp). *African Journal of Agricultural Research*. 6. 10.5897/AJAR11.1522.

Evett, S.R., Mazahrih, N.T., Jitan, M.A., Sawalha, M.H., Colaizzi, P.D., & Ayars, J.E. (2009). *A Weighing Lysimeter for Crop Water Use Determination In The Jordan Valley, Jordan*. Publications from USDA-ARS / UNL Faculty. 1813.

Ezlit, Y.D., Smith, R.J. & Raine, S.R. (2010). *A review of salinity and sodicity in irrigation*. The Cooperative Research Centre for Irrigation Futures. University of Southern Queensland.

Fares, A., & Alva, A.K. (2000). Soil Water Components Based on Capacitance Probes in a Sandy Soil. *Soil Science Society of America Journal.* 64 (1)**,** 311–318.

Fares, A., Awal, R., & Bayabil, H. K. (2016). Soil Water Content Sensor Response to Organic Matter Content under Laboratory Conditions. *Sensors (Basel, Switzerland), 16*(8), 1239.

Flowers T.S., & Yeo A.R. (1989). Effects of Salinity on Plant Growth and Crop Yields. In: Cherry J.H. (eds) Environmental Stress in Plants. *NATO ASI Series (Series G: Ecological Sciences)*, vol 19. Springer, Berlin, Heidelberg.

Flowers, T. J. (2004). Improving crop salt tolerance. *Journal of Experimental Botany*. 55(396), 307–319.

Gardener, C.M.K., Robinson, D., Blythe, K., & Cooper, J.D. (2000). *Soil Water Content* In Soil and Environmental Analysis: Physical Methods (Second Edition) Edited by Keith A. Smith and Chris Mullins Marcel Dekker.

Grattan, S. (2002). Irrigation water salinity and crop production. *Farm water quality planning (Factsheet)*. Publication 8066. University of California.

Grattan, S.R., & Grieve, C.M. (1999). Salinity-mineral nutrient relations in horticultural crops, *Scientia Horticulturae,* vol. 78 (pg. 127-157).

Gregory, P. (2006). Roots, rhizosphere and soil: the route to a better understanding of soil science? *European Journal of Soil Science*, 57: 2-12. doi:10.1111/j.1365-2389.2005.00778.x

Hamza, M.A., & Anderson, W.K. (2005). Soil compaction in cropping systems A review of the nature, causes and possible solutions. *Soil & Tillage Research* 82 (2005) 121–145.

Hanson, B., Schwankl, L. & Fulton, A. (2004). *Scheduling Irrigations: When and how much water to apply*. Water Management Series. Publication 3396. Davis, California, Department of Land, Air and Water Resources, University of California.

Harvey, B., & Strudwick, J. (2009). *Soil salinity build-up and expansion of recycled water use in the North Adelaide Plains*. Civil Engineering Honours Project, University of Adelaide, South Australia.

Imeson, A.C., & Kwaad, F.J. (1990). The response of tilled soils to wetting by rainfall and the dynamic character of soil erodibility, In *Soil erosion on agricultural land*, Boardman J, Foster IDL, and Dearing JA. (eds). John Wiley: Chichester; 3-14.

Irmak, S., Payero, J.O., Eisenhauer, D.E., Kranz, W.L., Martin, D.L., Zoubek, G.L., Rees, J.M., VanDeWalle, B., Christiansen, A.P., & Leininger, D. (2006). *Watermark granular matrix sensor to measure soil matric potential for irrigation management*. University of Nebraska. Lincoln Extension Circular EC783, 1–8.

Jackson, R.D. (1973). Diurnal changes in soil water content during drying. *Field Soil Water Regimes*, pp. 37–55. Soil Science Society of America. Madison, Wisconsin.

Kennedy, J. R., Keefer, T. O., Paige, G. B., & Barnes, E. (2003). Evaluation of dielectric constant-based soil moisture sensors in a semiarid rangeland. In *Proceedings of the First Interagency Conference on Research in the Watersheds (ICRW)*, 503–508.

King, B.A., & Stark, J.C. (2005). *Spatial variability considerations in interpreting soil moisture measurements for irrigation scheduling*. Extension Bulletin No. 837. University of Idaho. Retrieved from http://www.cals.uidaho.edu/edComm/pdf/BUL/BUL0837.pdf

Lantzke, N. (1995) *Nitrates in the groundwater beneath horticultural properties*. Department of Agriculture and Food, Western Australia, Perth.

Lantzke, N.C. (1997). *Phosphorus and nitrate loss from horticulture on the Swan Coastal Plain*. Department of Agriculture and Food, Western Australia, Perth. Report 16/97.

Lantzke, N., & Calder, T. (2004). *Water salinity and crop irrigation*. Farmnote No. 34, Department of Agriculture and Food, Western Australia.

Lantzke, N., Calder, T., Burt, J., & Prince, R. (2007). *Water salinity and plant irrigation*. Farmnote No. 234, Department of Agriculture and Food, Western Australia.

Lehrsch, G.A., & Kincaid, D.C. (2006). Sprinkler droplet energy effects on soil penetration resistance and aggregate stability and size distribution. *Soil Science* 171:435–477.

Libutti, A., & Monteleone, M. (2012). Irrigation management in Mediterranean salt affected agriculture: How leaching operates. *Italian Journal of Agronomy.* 7(1), 28–35.

Lovell, J. (2006). *Guidelines for Environmental Assurance in Australian Horticulture.* Horticulture Australia Ltd, Sydney.

Maas, E.V., & Hoffmann, G.J. (1977). Crop salt tolerance–current assessment. *Journal of the Irrigation and Drainage Division.* 103, 115–134. American Society of Civil Engineers (ASCE).

Mackay, A. (2014). *Carrots in Western Australia.* Retrieved from https://www.agric.wa.gov.au/carrots/carrots-western-australia

McArthur, W.M. (2004). *Reference Soils of south-western Australia*. Department of Agriculture, Western Australia, Perth.

McCauley, A. (2005). *Water and solute transport in soils*. Soil and water management Module 4. Montana State University.

Meagher, T. (2010). *Annual Monitoring Review, 2008/10 Coast Pastoral Company Pty Ltd Locations 17, 20 & 48 Old Coast Rd, Myalup*. Client Report, Perth, Western Australia.

Meyer, W.S., & Bowmer, K.H. (2004). Sustainable irrigation. *Water Innovation: A New Era for Australia*, 104–125. CL Creations, Sydney.

Moiwo, J.P., & Tao, F. (2015). Contributions of precipitation, irrigation and soil water to evapotranspiration in (semi)-arid regions. *International Journal of Climatology*. 35: 1079–1089.

Money, R. (2000). *Scheduling irrigation of potatoes using tensiometers on light/medium to heavy soils*. Farmnote, No. 107. Department of Agriculture and Food, Western Australia.

Monteleone, M., & Libutti, A. (2012). Salt leaching due to rain in Mediterranean climate: is it enough? *Italian Journal of Agronomy*, 7, (1) 36–43. Retrieved from http://www.agronomy.it/index.php/agro/article/view/ija.2012.e6/416

Mullins, C. (2000). Matric Potential. In Smith K.A and Mullins C.E. (eds) *Soil and Environmental Analysis: Physical Methods*. 2nd ed. Marcel Dekker, New York.

Murray, R.S., & Grant, C.D. (2007). The Impact of Irrigation on Soil Structure. The National Program for Sustainable Irrigation (Land & Water Australia) Publ., Braddon, Australia.

Naughton, S. (2009). *Total dissolved salt movement throughout sprinkler irrigated ground water in the South West of Western Australia*. DSR Project 2009. University of Notre Dame Australia.

O'Malley, P., & Prince, R. (2010). *Optimising water and nutrient use on vegetable Farms.* Retrieved from http://ausveg.com.au/intranet/technical-insights/docs/VG08020.pdf

Odyssey Dataflow Systems. (2014). Odyssey Product Range. Retrieved from http://odysseydatarecording.com/index.php?route=common/home

Oster, J.D. (1994). Irrigation with poor quality water. *Agricultural Water Management*, Vol. 25, issue 3, 271-297.

Phillips, D. (2005). *Carrot nutrition and irrigation*. Farmnote, No. 94/90. Department of Agriculture and Food, Western Australia.

PIRSA – see Primary Industry and Resources South Australia.

Platts B., & Grismer, M. (2014). Rainfall leaching is critical for long-term use of recycled water in the Salinas Valley. *California Agriculture*. 68(3):75-81. https://doi.org/10.3733/ca.v068n03p75.

Primary Industry and Resources South Australia (PIRSA). (2006). *Monitoring soil salinity for irrigated horticulture 2006.* Retrieved from http://www.pir.sa.gov.au/__data/assets/pdf_file/0008/39599/Monitoring_Soil_Salinity_for_Irrigated_Horticulture.pdf

Prince, R., O'Malley, P., Mackay, A., Calder, T., & Deyl, R. (2008). *Vegetable farming on the beach - improving irrigation scheduling to avoid the environmental backwash*. Department of Agriculture and Food, Western Australia. Retrieved from http://irrigation.org.au/documents/publications-resources/conference_papers_2008/Paper_Vegetable_Farming_on_the_Beach.pdf

Rana, G., & Katerji, N. (2000). Measurement and Estimation of Actual Evapotranspiration in the Field under Mediterranean Climate: A Review. *European Journal of Agronomy*, 13, 125-153.

Rayment, G.E., & Higginson, F.R. (Eds). (1992). *Australian Laboratory Handbook of Soil and Water Chemical Methods*. Inkata Press. Melbourne.

Rhoades, J.D., Chanduvi, F., & Lesch, S. (1999). *Soil salinity assessment: Methods and interpretation of electrical conductivity measurements*. Irrigation and Drainage Paper, No. 57. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Rockwater Pty Ltd. (2000). *Australind – Eaton waste water study modelling ground water flows from planned woodlot*. Client Report. Perth, Western Australia.

Rockwater Pty Ltd. (2009). *Dawseville to Binningup Technical Environmental Studies – Hydrogeological Study.* Report for the Department of Environment and Conservation. Jolimont, Western Australia.

Rowe, D., Tille, P., & Kuswardiyanto, K. (2017). Land capability assessment for expanding irrigated horticulture around Myalup. *Resource management technical report 400*, Department of Primary Industries and Regional Development, Perth.

Schoups, G., Hopmans, J.W., Young, C.A., Vrugt, J.A., Wallender, W.W., Tanji, K.K., & Panday, S. (2005). Sustainability of irrigated agriculture in the San Joaquin Valley, California. In *Proceedings of the National Academy of Sciences*, USA 102, 15352–15356.

Semeniuk, V. (1995). New Pleistocene and Holocene stratigraphic units in the Yalgorup Plain area, southern Swan Coastal Plain. *Journal of the Royal Society of Western Australia*, 78 (3), 67–79.

Semeniuk, V. (1997). Pleistocene Coastal Palaeogeography in Southwestern Australia – Carbonate and Quartz Sand Sedimentation in Cuspate Forelands Barriers and Ribbon Shoreline Deposits. *Journal of Coastal Research,* 13:2, 468–489.

Shainberg, I., & Letey, J. (1984). Response of soil to sodic and saline conditions. *Hilgardia*, 52, 1-57.

Shannon, M. C., Grieve, C. M., & Francois, L. E. (1994). *Whole-plant response to salinity*. In Plant-Environment Interactions (R. E. Wilkinson, Ed.), pp. 199-244. Dekker, New York.

Shannon, M.C., & Grieve, C.M. (1999). Tolerance of vegetable crops to salinity. *Scientia Horticulturae,* 78, 5–38.

Sheldon, A., Menzies, N.W., Bing, S.H., & Dalal, R.C. (2004*). The effect of salinity on plant available water*. Supersoil 2004: 3rd Australian New Zealand soil conference.

Shi, T. T., Guan, D.X., Wu, J.B., Wang, A.Z., Jin, C.J., & Han S.J. (2008). Comparison of methods for estimating evapotranspiration rate of dry forest canopy: Eddy covariance, Bowen ratio energy balance, and Penman-Monteith equation, *J. Geophys. Res.*, 113, D19116.

Smith, A., & Hick, W. (2001). *Hydrogeology and aquifer tidal propagation in Cockburn Sound, Western Australia*. CSIRO Land and Water Technical Report 06/01.

Smith, K. A., & Mullins, C. E. (2000). *Soil and Environmental Analysis: Physical Methods* (2nd Ed). CRC Press, New York.

Starr, J.L., Timlin, D.J., Downey, P.M., & McCann, I.R. (2009). Laboratory evaluation of dual-frequency multisensor capacitance probes to monitor soil water and salinity. *Irrigation Science.* 27(5), 393–400.

Sumner, D.M., & Jacobs, J.M. (2005). Utility of Penman–Monteith, Priestley–Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration, *Journal of Hydrology*, Volume 308, Issues 1–4, 81-104.

Tedeschi, A., & Dell’Aquila, R. (2004). Effects of irrigation with saline waters, at different concentrations, on soil physical and chemical characteristics. *Agricultural Water Management*, 77 (2005) 308–322.

Topp, G.C., Davis, J.L., & Annan, A.P. (1980). Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resources Research.* 16: 574–582.

Uddin, J., Smith, R., Hancock, N., & Foley, J. (2014). *Are evaporation losses in sprinkler irrigation high?* In: 17th Australian Cotton Conference (ACC 2014): Our Fibre, Our Focus, Our Future, 5-7 Aug 2014, Gold Coast, Australia.

Villagarcía, L., Were, A., Cantón, Y., Fernández, F., Moro, M.J., Domene, M.A., Solé-Benet, A., & Domingo, F. (2004). Daily soil water content fluctuations in rangelands from semi-arid SE Spain. *ERB2004 – Euro-Mediterranean Conference*, Turin, Italy.

Walker, J.P., Willgoose, G.R., & Kalma, J.D. (2004). In situ measurement of soil moisture: A comparison of techniques. *Journal of Hydrology*. 293(1–4), 85–99.

Warrence, N., Bauder, J.W., & Pearson, K.E. (2002). Basics of Salinity and Sodicity Effects on Soil Physical Properties.

Zazueta, F.S., & Xin, J. (1994). *Soil Moisture Sensors*. Bulletin 292. Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.

Zekri, M., Núñez-Elisea, R., Schaffer, B., O’Hair, S.K. & Crane, J.H. (1999). Multi-sensor capacitance probes for monitoring soil water dynamics in tropical fruit orchards in south Florida. *Proceedings of the Florida State Horticultural Society*112:178–181.

Zeleke, K. & Wade, L. (2012). Evapotranspiration Estimation using Soil Water Balance, Weather and Crop Data. In A. Irmak (Ed.), *Evapotranspiration: Remote Sensing and Modeling* (1 ed.), 41-58.